THE EFFECT OF A PERFORATED PLATE ON THE FLOW OF AIR BUBBLES IN A QUIESCENT LIQUID

by

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INTRODUCTION

Since the advent of nuclear energy as a means of producing electric power, many developments have been made to produce this power more economically so that it may be competitive with fossil fuel plants. Among the major developments of this program has been the design of a boiling water nuclear reactor with integral nuclear superheating. In this arrangement a conventional boiling water reactor is used with its central portion usually serving as a superheat region, thus forming a two-pass system.

Two of the main problems encountered in the design of a superheat nuclear reactor are steam "carryunder" and water "carryover" in the system. "Carryunder" is that steam which is entrained in the boiling water and recirculated through the boiler region. This condition is undesirable because it can cause excessive void formation in the core. The problem has been satisfactorily solved through the development of vortex steam separators for use in the reflector region, but work is being done to improve this method.

Little research has been done to solve effectively the problem of water droplet "carryover" in the steam leaving the boiler region. The reduction of "carryover" is needed to eliminate the erosion of the superheater structure and fuel elements due to the impingement of high velocity water droplets and to prevent the introduction of corrosive materials to the high temperature region. One solution currently being utilized consists of stainless steel mesh, located above the boiling interface, which traps water droplets. The efficiency of this mesh, however, is dependent upon the size of water droplets introduced to it. It has been noted by Grenda and Wilson (18) that the water droplet entrainment is reduced if smaller bubbles are presented to the boiler interface. A method for reducing the large bubbles which originate in the core would be to install perforated plates.

The problem investigated in this thesis is that of the effect of a perforated plate on the flow of bubbles. For this study air bubbles have been used to simulate steam bubbles in the boiler. The effects which are considered are bubble break up, pressure drop, coefficient of discharge, void fraction and changes in void fraction and flow regimes due to the presence of a perforated plate.

LITERATURE REVIEW

The literature on bubble flow in liquids, as well as formation of bubbles at an orifice, was found to be extensive. However, no investigation treated the problem of bubbles flowing through a perforated plate directly. The review presented here has been divided into two sections which deal in turn with single bubbles formed at single holes and the problem of bubble flow through a multiple hole plate.

Single Bubble Phenomena

R. S. Brown (1) studied the problem of bubbling from perforated plate trays equipped with downcomers for use in distillation apparatus. He presents an empirical formula for the prediction of the bubble frequency from a perforated plate based on the diameter and area of the hole, thickness of the plate, and volume of the chamber beneath the plate. It was pointed out that a theory of bubble flow is all but impossible to develop due to the difficulty in solving the complex equations involved. Brown also found that as the orifice diameter was reduced the bubble frequency increased and that an increase in chamber volume increased the frequency of bubble formation. He did not find an appreciable effect on pressure fluctuations due to an increase of liquid head above the plate.

A qualitative study of bubbling from the tip of a submerged glass tube was made by Datta, Napier and Newitt (2). They noted that bubbles formed at orifices up to 0.04 cm. in diameter are substantially spherical and upon release from the plate momentarily exceed the terminal velocity. For orifices between 0.04 to 0.4 cm. in diameter, the bubbles were spherical at release but became ellipsoidal with the major axis in the horizontal plane. They also found there was no typical bubble size for a given orifice and that hydrostatic head had very little influence upon rate of formation and bubble size.

Davidson (3) studied extensively the problem of bubbling from a submerged orifice. He developed a theory for static as well as dynamic bubbling from an orifice. Results were presented in two forms which were the frequency and bubble volume plotted against the flow rate. The purpose of these types of plots was to show the "constant frequency" phenomenon at high flow rates in which bubble volume increases directly as the flow rate, while the volume curve gives a better description of bubbling at low flow rates.

In continuation of work already mentioned, Davidson and Amick (4) studied the frequency of bubbles from a perforated plate. They noted the effect of the volume of the chamber below the orifice upon bubble frequency. An empirical equation for the maximum frequency of bubble formation, n_m (bubbles/sec.), based on flow rate, q (ft.^{3}/sec.), and hole radius, r (ft.), was found to be

$$n_m = 9.1 \quad q^{0.13} \;/\; r^{0.45} \qquad (1)$$

Much work on the rise of bubbles in liquids was done by Haberman and Morton (7) and Rosenberg (13). They found that the velocity of rise, bubble shape, path and general kinetic behavior depend upon bubble size (volume), pressure gradient, density and viscosity of the medium and, to a lesser extent, on the surface tension. Rosenberg developed an empirical formula for wall correction to find the terminal velocity, U (ft./sec.), of a single bubble as well as a formula for the rate of rise of a spherical cap bubble based on the radius of curvature of the nose, R (ft.), and the gravitational constant, g (ft./sec.^{2}),

$$U = 0.645 \sqrt{gR} \qquad (2)$$

Haberman and Morton carried the same studies further by using various liquids to find the effects of viscosity, density, and surface tension.

A linear correlation between the pressure drop across a perforated plate and the square of the velocity of the gas passing through it was found by Hunt (9).

Peebles and Garber (11) studied the motion of gas bubbles in a liquid and found that the shape of a bubble is dependent upon the Reynolds number. They also developed a correlation for flattened ellipsoidal bubbles as well as an equation to predict the terminal velocity of mushroom type bubbles which have a Reynolds number greater than 1500.

Uno and Kintner (15) investigated the retarding effect of a wall on bubble terminal velocity and derived a relationship to correct this effect. To make the wall effect negligible, the minimum diameter of a tube should be ten times the equivalent diameter of the largest bubble which will be studied.

The acknowledged founders of a theoretical basis for bubble formation are Van Krevelen and Hoftijger (16). They recognized two types of bubbling which are single and chain. By dimensional analysis they were able to conclude that bubble size is independent of flow rate.

Multiple Bubble Phenomena

A study of air-water flow in 1.025 inch diameter pipe was made by Govier, Radford and Dunn (6). They developed their studies from the assumption that two-phase flow is not a simply described phenomena with definite laminar, transition and turbulent flow regions nor does it maintain a constant composition along its path. Using their own data and that of other researchers they were able to divide the types of flow into regimes. They found that for a pressure drop of about 0.2 feet of water per foot of travel there was a transition from bubble to slug flow in an air-water system. This transition exists in the first flow regime at low flow rates.

Hughes *et al*. (8) made a study of bubbles formed at a tube inserted in a plate. They performed their investigations in the regions of low flow rate, intermediate flow rate where bubble size is dependent upon the flow rate and in the high flow region where bubble break up is random. It was also found that as chamber volume increased the bubble size increased.

Leibson _et al_. (10) found discharge coefficients for circular submerged orifices based on the flow of an ideal gas. They also did an extensive qualitative study of bubble flow from low to very high Reynolds numbers. At Reynolds numbers greater than 10,000 the larger bubbles were found to shatter about 3 to 4 inches above the orifice.

Two-phase flow phenomena in a rectangular duct was investigated by Petrick (12). The object of his work was to determine flow distribution of air water systems after abrupt charges in flow area. He found that flow became annular with the air forming an annulus around a more dense center core.

Sterman (14) presented a dimensional evaluation of steam-water phenomena. He found that for a given distance above a perforated plate used in his studies, the void fraction remained constant. Viscosity was not found to be a variable which affects the void fraction in a perceptible manner. Using dimensional analysis he developed the correlation formula for the void fraction

$$\alpha = K\left(\frac{\rho_g}{\rho_f-\rho_g}\right)^{0.17}\left[\frac{\sqrt{\frac{\sigma}{g(\rho_f-\rho_g)}}}{d}\right]^{0.25}\left[\frac{V_s}{\left(g\sqrt{\frac{\sigma}{g(\rho_f-\rho_g)}}\right)^{1/2}}\right]^{a} \quad (3)$$

where
α = steam volume fraction
V_s = superficial steam velocity
σ = surface tension of the liquid
ρ_f = density of fluid
ρ_g = density of steam
d = vessel diameter
g = acceleration due to gravity

Using data of other investigators, coupled with his own, he found that K was 1.07 when "a" became 0.4 for a steam-water mixture.

Verschoor (17) injected a stream of bubbles into a column and studied their flow. He developed a formula for the average bubble velocity as a function of void fraction, average gas velocity and vessel area.

In still another study by Wilson, Grenda and Patterson (19), the exponential of the first and second terms became 0.32 and 0.19 respectively. These values were chosen since the resultant empirical equation seemed to fit their data best. However, this equation did not agree well with the data of a previous investigation.

Utilizing the method developed by Sterman in the correlation of steam-water data, Wilson, Grenda and Patterson (20) found that their data were best correlated by the equation

$$\alpha = K\left(\frac{\rho_g}{\rho_f-\rho_g}\right)^{0.17}\left[\frac{\sqrt{\dfrac{\sigma}{g(\rho_f-\rho_g)}}}{d}\right]^{0.1}\left[\frac{V_s}{\left(g\sqrt{\dfrac{\sigma}{g(\rho_f-\rho_g)}}\right)^{1/2}}\right]^{a} \tag{4}$$

where the terms are the same as those defined previously. It should be noted that the second term exponential has been lowered from 0.25 to 0.1 due to added data gathered over a wider range of vessel diameters. In this study it was found that a break occurred when the third term equalled 2. When this term was less than 2, K equalled 0.68 and "a" became 0.62. For a value larger than 2, K was 0.88 while "a" equalled 0.40.

OBJECTIVES OF THE INVESTIGATION

The further development of boiling water nuclear reactors, especially those with nuclear superheating, is dependent upon the design of effective means of limiting steam "carryunder" and water droplet "carryover" to increase thermodynamic efficiencies as well as to increase the life of superheater components. Design of better mechanical steam dryers necessitates a greater knowledge of two-phase flow phenomena and the effect which a perforated plate has on the break up of bubbles, so that smaller bubbles may be produced which will minimize water droplet generation at the boiling interface.

It is the purpose of this investigation to study bubble break up on a "microscopic" and "macroscopic" basis. The "microscopic" study will be concerned with a qualitative analysis of the passing of a single bubble through a single hole. The "macroscopic" study will be conducted with a multiple hole plate and much higher flow rates. Points which will be investigated include the effect of the various sized perforated plates on the types of flow formed, bubble distribution and size, and void fraction at the center of the column. The investigation will also encompass the determination of the coefficients of discharge of the plates as well as the pressure drop. Results obtained will then be correlated with the equation developed by Sterman (14) with the modifications found by Wilson <u>et al</u>. (20) to determine how these results compare with steam water systems. If a correlation does in fact exist then these results should be applicable to such systems.

EXPERIMENTAL APPARATUS AND PROCEDURES

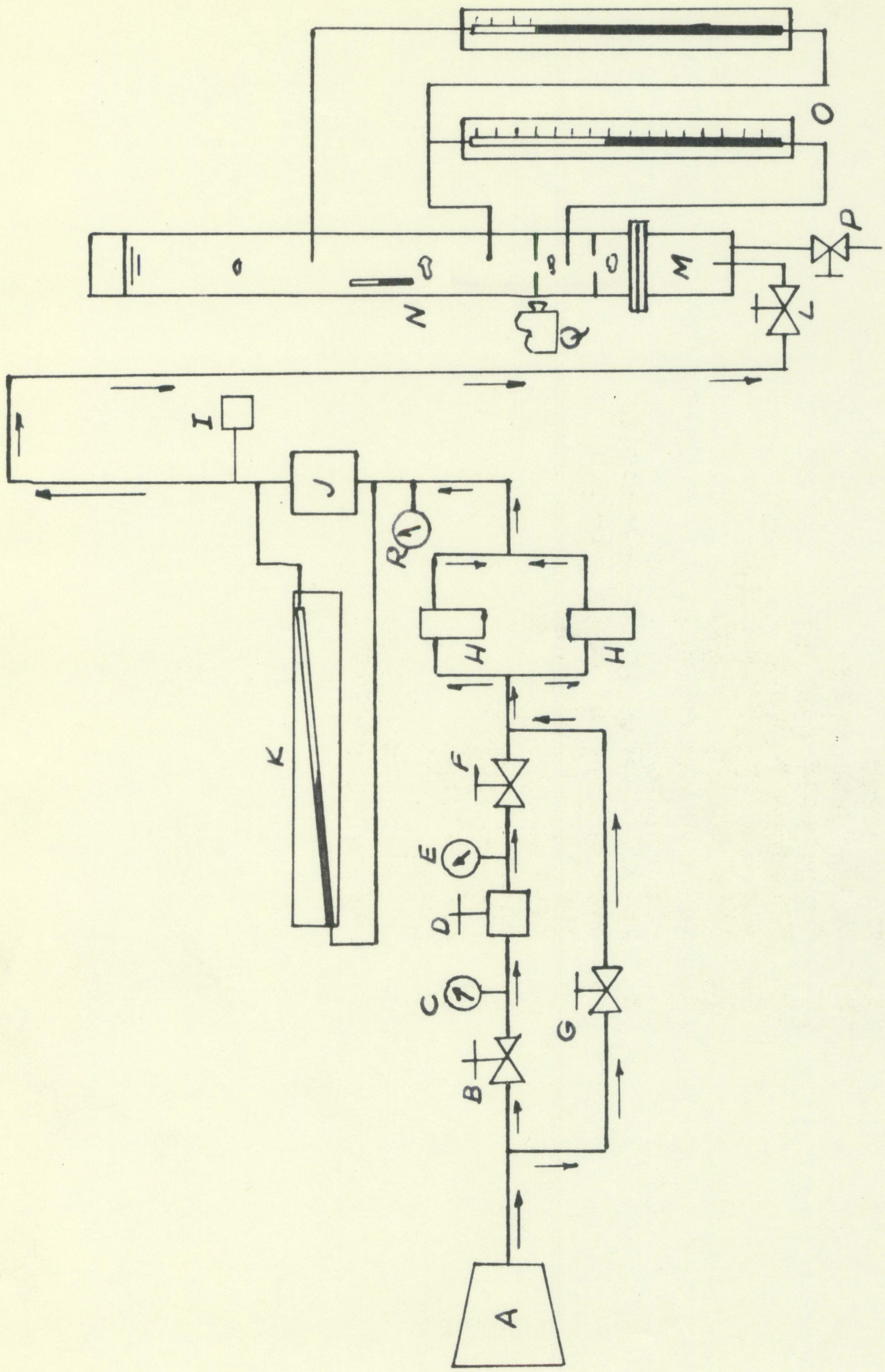
The experimental apparatus used in this study was designed with two purposes in mind. The first was that it be used to generate single bubbles of more or less uniform size for the investigation of the action of a single bubble as it passed through a circular submerged orifice. Secondly, it should be easily adaptable to the higher flow rates employed in the study of bubble flow through a perforated plate.

A schematic diagram of the apparatus used is shown in Figure 1. This diagram shows all of the components used in the single bubble and hole studies as well as for the multiple hole tests.

A rotary compressor (A) supplied air to the system at approximately 100 psig. The initial flow was controlled by a 3/4 inch valve at (B) which permitted the air to flow to a pressure reducer. Ashcraft pressure gages were placed at (C) and (E) to measure the pressure before and after the pressure reducer. A 2 inch valve placed at (F) controlled the flow of air entering the air cleaners. Also included was a bypass line and valve (G) which was used to clean the system before and after each run. Two Fulflo air filters were used at (H) to remove dirt and oil from the air before it entered the flow meter (J). A Heise pressure gage with a range of 150 psig. in 0.25 psig. subdivisions was used to obtain a more accurate

Figure 1. Flow diagram of apparatus

A. Compressor
B. Compressor valve
C. Compressor reducer
D. Pressure reducer
E. Reduced pressure gage
F. Flow control valve
G. Reducer bypass valve
H. Air filters
I. Potentiometer and thermocouple
J. Meriam laminar flow element
K. Inclined manometer
L. Fine control valve
M. Inlet manifold
N. Thermometer
O. Manometers
P. Drain
Q. 16 mm movie camera
R. Air inlet pressure


A
B
C
D
E
F
G
H
H
I
J
K
L
M
N
O
P
Q
R

determination of the pressure before entering the test region. A Merriam Laminar Flow Meter, type W, with its accompanying inclined manometer was used to measure the amount of air flowing to the test section. The temperature of the air was measured by a thermocouple and potentiometer place at (I).

To provide a fine control of air flow into the test section a needle valve was placed at (L). This valve was primarily used during the single-hole tests and was left open for the multiple-hole experiments.

The air was introduced into a sheet metal manifold through a 3/4 inch pipe. As the air flowed upward it first encountered an entrance plate placed 6 inches below the test plate. The purpose of this entrance plate in the case of the single-hole study was to guide the bubble into the orifice of the test plate. For the multiple-hole plate, an inlet plate with sixteen 3/4 inch diameter holes on 1 inch centers served to distribute the bubbles entering the test plate. A thermometer (N) was placed in the water to determine its temperature. For measuring the pressure drop across the test plate, manometer taps were located 3 inches below and above the plate. The void fraction measurement was determined by a third manometer tap placed 15 inches above the second tap. The air was then vented to the atmosphere at the open top of the column after passing the test section.

The drain valve located at the bottom of the inlet manifold served two purposes. The primary purpose was to drain the column of water after each run. Secondly, it was also used in adjusting the height of the two phase interface in the multiple hole tests.

The general dimensions of the apparatus are shown in Figure 2. The inlet manifold was constructed of 0.20 inch steel sheet metal with a 1/4 inch welded flange. The test column itself was built from a 53 inch tube of acrylic plastic with an outside diameter of 6.0 inches and an inside diameter of 5.75 inches. The locations of the manometer taps with respect to the test plate and inlet plate are also shown.

Perhaps the most difficult design problem encountered was that of developing a single bubble generating system. Originally the apparatus was designed without the inlet plate. Despite the fact that the 3/4 inch pipe could generate a single bubble it was found that after traveling approximately 13 inches the zig-zag line of rise caused the bubble to encounter the test plate well off center. This was corrected by mounting the test plate on metal rods 6 inches above an inlet plate consisting of a 1 inch hole drilled in a 1/8 inch plate. The purpose of this plate was to "guide" the bubble into the center of the test plate.

This method proved unsuccessful because its sharp corners caused the bubble to break up somewhat in its passage through the plate when it would hit off center. To eliminate the entrance of two or more bubbles a 1 inch length of 1 inch I.D. tubing was brazed to the underside of the inlet plate. The air collected underneath the plate was then bled off through a valve (not shown in Figure 2). This method succeeded in introducing only one bubble to the test plate but produced a wide range of bubble sizes which was unsatisfactory.

The final modification made to the inlet plate was to permit the volume under the plate up to the 1 inch tube extension to fill completely with air. Thus, when an incoming bubble hit off center the bubble would slide off this cushion due to surface tension effects and the bubbles formed were of a uniform size and only one was generally produced.

The test plates for the single hole test were constructed of 0.035 inch galvanized steel of 5-3/4 inches diameter. Plates were made with 3/4, 1/2, 1/4, and 1/8 inch diameter holes drilled in the center. Preliminary tests showed that these flat plates collected bubble fragments underneath and these interfered with other incoming bubbles. This was corrected by making the plates conical with the apex in the center of the plate. The height of the cone thus formed was 1/4 inch with a base of approximately 5-3/4 inches.

Test plates for the multiple hole tests were constructed of the same 0.035 inch galvanized steel sheet with a 5-3/4 inch diameter. Each plate consisted of 16 holes drilled on 1 inch centers in a square array. This arrangement provided for only one variable in the test plate, which was the hole diameters and, thus, the total area drilled out. These plates were not conically formed due to the high flow rate and amount of holes involved.

For the study of single bubbles passing through a single hole a high speed camera was used. The camera used was an Arriflex 16 mm motion picture camera with a turret lens. For these pictures a close-up lens was used with the lens set at f11 at a distance of 2.25 feet. Lighting was provided by three lights. One, equipped with a diffuser, was placed directly behind the apparatus opposite the camera to provide a white background for the bubbles and cause them to be outlined in black so that they could be seen more easily. This system was used by Haberman and Morton (7) and Rosenberg (13) in their study of single bubbles. The other two lights were used to fill in shadows and to illuminate the stop watch used to provide a time scale. The camera was operated at a maximum speed of approximately 50 frames per second. A photograph of the apparatus, including lighting and camera arrangement is shown in Figure 3.

The water used in this experiment was tap water provided by the City of Greendale, Wisconsin, to the Greendale Laboratory of the Allis-Chalmers Manufacturing Company. An analysis of the water is provided in Table 1, where all values are in parts per million (PPM).

Figure 2. Cross section and dimensions of apparatus

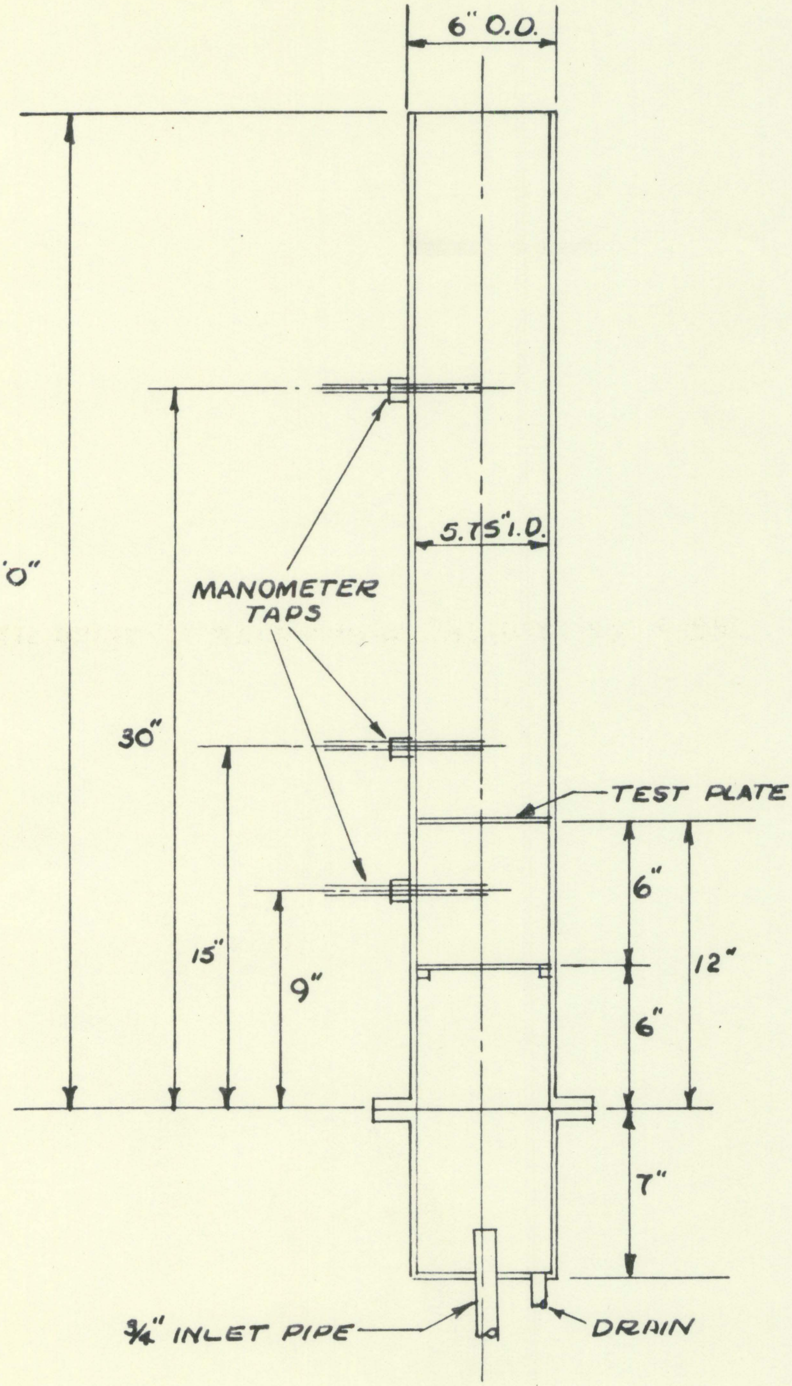

6" O.D.
5'0"
MANOMETER
TAPS
5.75" I.D.
30"
TEST PLATE
6"
12"
15"
9"
6"
7"
3/4" INLET PIPE
DRAIN

Figure 3. Photograph of test column

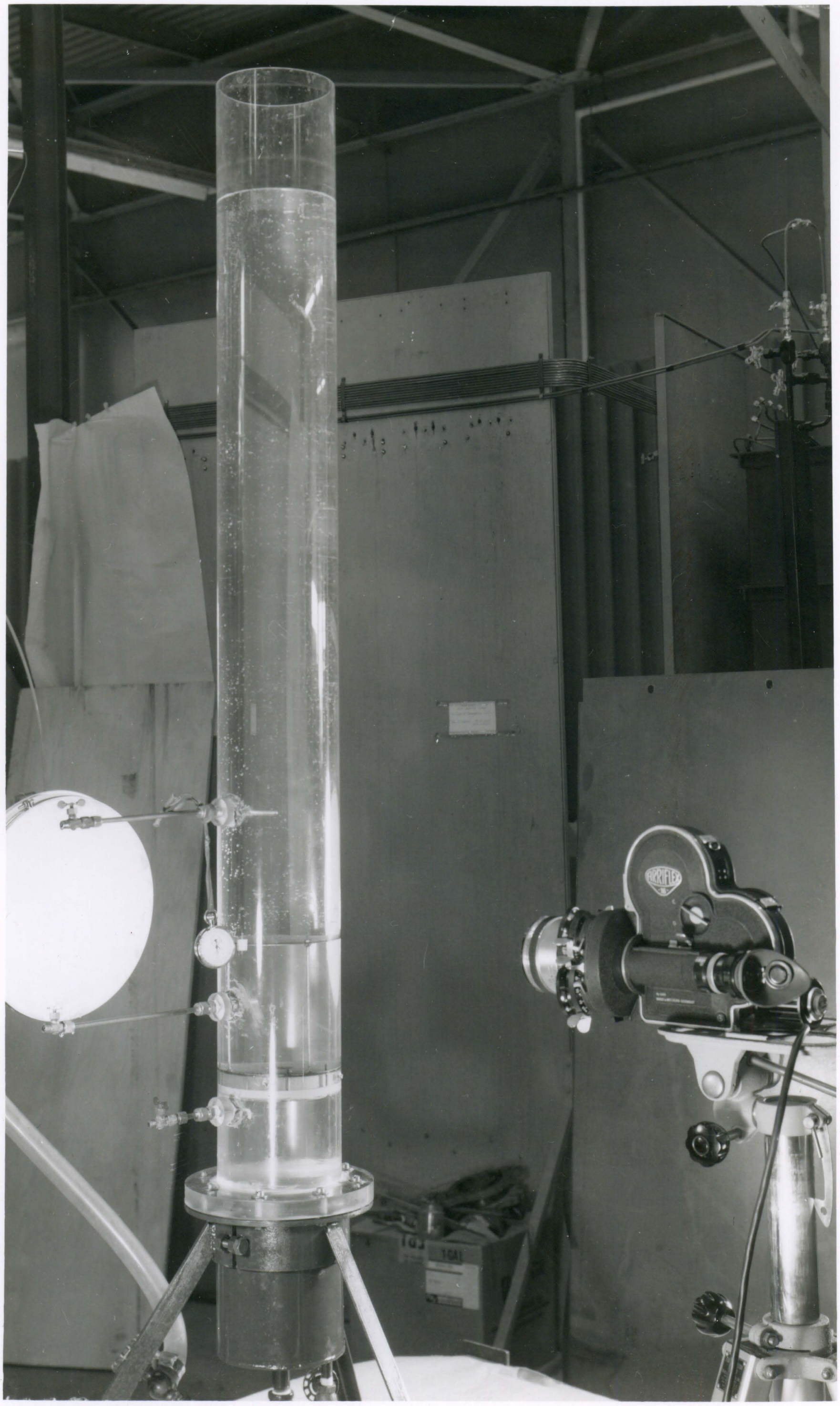


Table 1. Water analysis

Constituent	Amount PPM
Total Hardness ($CaCO_3$)	166
Calcium (Ca)	51
Magnesium (Mg)	9
"P" Alkalinity ($CaCO_3$)	0
Total Alkalinity "M" ($CaCO_3$)	214
Sulfate Hardness ($CaCO_3$)	0
Chloride (Cl)	12
Sulfate (SO_4)	245
Nitrate (NO_3)	0
Silica (SiO_2)	8.5
Iron (Fe_2O_3)	0.1
Bicarbonate (HCO_3)	261
Sodium (Na)	148
Total Dissolved Solids	602
pH	7.7

Procedure for Single Hole Tests

Since these tests involved the use of a high speed motion picture camera, it was decided to run it continuously while the bubbles were allowed to flow through the test plate. This eliminated the speed variations accompanying constantly starting and stopping the camera since the film speed, coupled with the stop watch, provided the time scale for each event recorded.

After mounting the test plate, the apparatus was filled with water and the height adjusted so that it was 3 feet above the flange or 2 feet above the test plate. Next the bypass valve was opened and the air cleaners blown out. After the air filters were cleaned, the fine control valve was opened and air was permitted to flow through the column to fill the volume beneath the inlet plate and to saturate the water to minimize the absorption of air during the actual test.

Next, the bubble generating frequency was adjusted in the following manner. The compressor valve to the pressure reducer was opened and the reducer was adjusted while the coarse control valve was open to allow the pulsing of the reducer's ball check valve to die out. The fine control valve was then adjusted to give the proper bubble frequency. When the proper frequency was attained the system was allowed to run for approximately one half hour to further insure the air saturation of the water as well as the stability of the frequency.

After the system had been allowed to stabilize the temperature of the air and water were recorded, as well as the pressure before and after the reducer plus the height of water above the test plate. When this was done the lights were turned on and the stop watch and camera started. The amount of film taken of each test was 100 feet, which included about sixty events recorded. After the filming was completed the air pressures and temperature and the water temperature were again recorded to make sure there were no great changes during the run.

When each test was completed the column was drained and removed from the manifold and the next test plate installed. The manifold, and its stand, remained stationary, as well as the camera position, during all tests so that the timing and scaling film made at the completion of all runs could be applied to each test. This test movie provided the scale for measuring bubble size and velocity.

Multiple Hole Test Procedure

The test procedure for the multiple hole study was not as complicated as that for the single hole investigation since it was not necessary to maintain a constant bubble frequency but only a constant flow rate.

When the test plate was installed in the column it was filled nearly to the top so that the manometers could be adjusted. This portion of the multiple hole test was important because it is necessary that all lines of the manometer system be completely filled with water so that accurate pressure readings could be obtained. The lines were filled with water from the test column.

After the manometers were adjusted the air flow was turned on. Air was permitted to flow through the test water for approximately ten minutes to saturate it with air and to test the manometers. The air flow was then set to correspond with the first reading needed and the bubbling interface was adjusted by eye to be approximately 2 feet above the test plate.

The condition was then allowed to run for about 2 minutes and readings taken. Those readings recorded were the inclined manometer reading to determine the flow rate through the flow meter, air temperature, air pressure, water temperature and the two manometer readings. The flow rate was then adjusted for the next desired reading and the procedure repeated until it was no longer possible to keep the water from splashing out of the column or the volume beneath the test plate became voided.

RESULTS

Single Hole Test

Difficulty was encountered in accurately evaluating the motion pictures taken of single bubble flow because of poor resolution of the viewer. Despite this difficulty it was possible to make a qualitative study of the phenomena of bubble flow through plates containing holes of 3/4, 1/2, 1/4 and 1/8 inches in diameter.

The shape of the bubbles entering the test plate followed the description given by Haberman and Morton (7) and Rosenberg (13). The bubbles were spherically capped or ellipsoidal in shape and rose with a side to side motion. Although the bubbles apparently kept their general shape during their rise, the motion pictures showed that their surface was deformed and the bubble shape changed continually during the rise of the bubble. The terminal velocity of the incoming bubbles agreed rather well with the results of Haberman and Morton (7) for the rise of air bubbles in tap water. It is felt that the spacing of the bubbles was sufficient to minimize drag effects during the tests because of the constancy of the velocity found for bubbles of the same dimensions.

Since it was not possible to reproduce the pictures taken of single bubble flow, the description following will be illustrated by showing the displacement of each bubble as a function of time. The distance plotted in each case is the distance from the bottom of the picture frame to the top of the bubble. The deformed surface mentioned earlier accounts for the not-quite-linear relationship. In each case a particular event is presented which represents the most common occurrence for the hole diameter under consideration.

During the study of bubble flow through a plate containing a 3/4 inch hole, 66 individual events were recorded. An event means the history of a single bubble from the time it comes into the field of vision to the time it leaves the field. Bubble diameters were generally in the range of 0.70 to 0.85 inches while bubble heights varied from 0.20 to 0.30 inches. The traverse of a single bubble of 0.85 inches in diameter is shown in Figure 4. Pertinent data are shown on the facing page of the graph and include film speed, event, and incoming and outgoing bubble dimensions and velocities. Since the bubble diameter was approximately the same as that of the hole, the bubbles readily passed through the holes. In most cases the bubble was found to contract in diameter and to elongate. Bubble break up was noted in only two events when the bubble encountered the plate well off center.

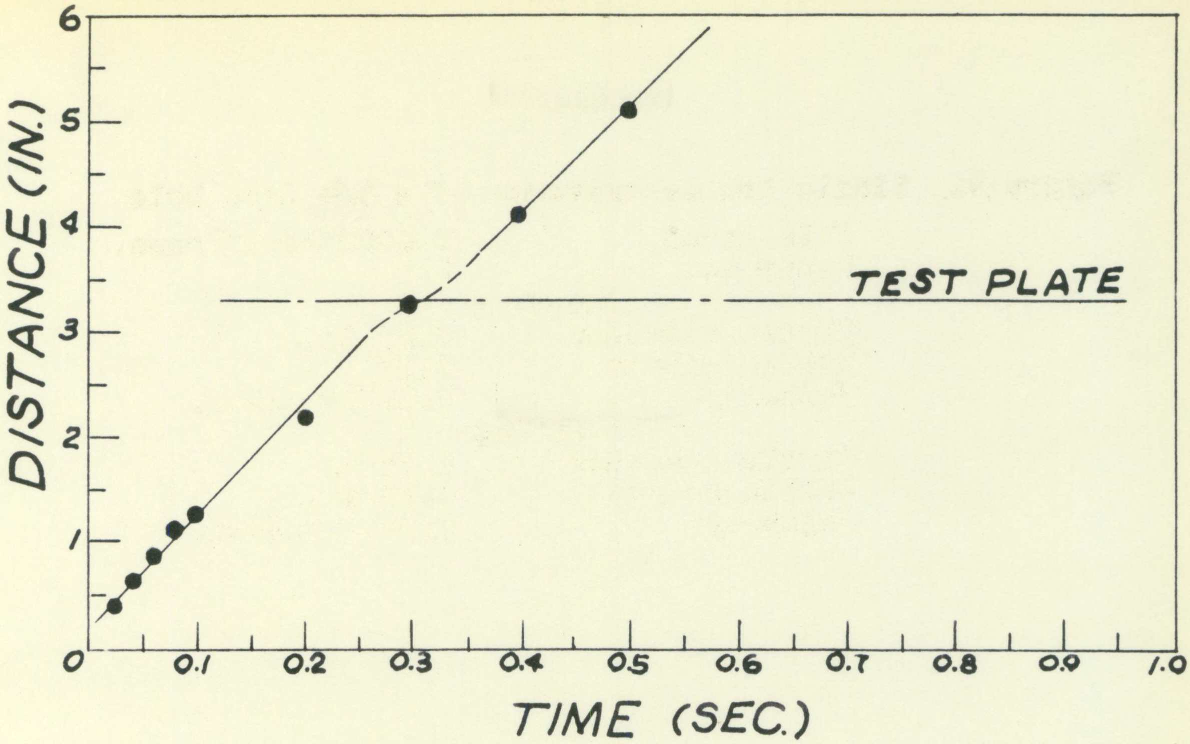
Figure 5 shows the traverse of a single bubble through a hole of 1/2 inch diameter. There were 67 events recorded in this study. In this case the graph represents what appears to be only one bubble after passing through the hole. This was not true, however. During the filming of these events it was

Figure 4. Single bubble traverse of a 3/4 inch hole

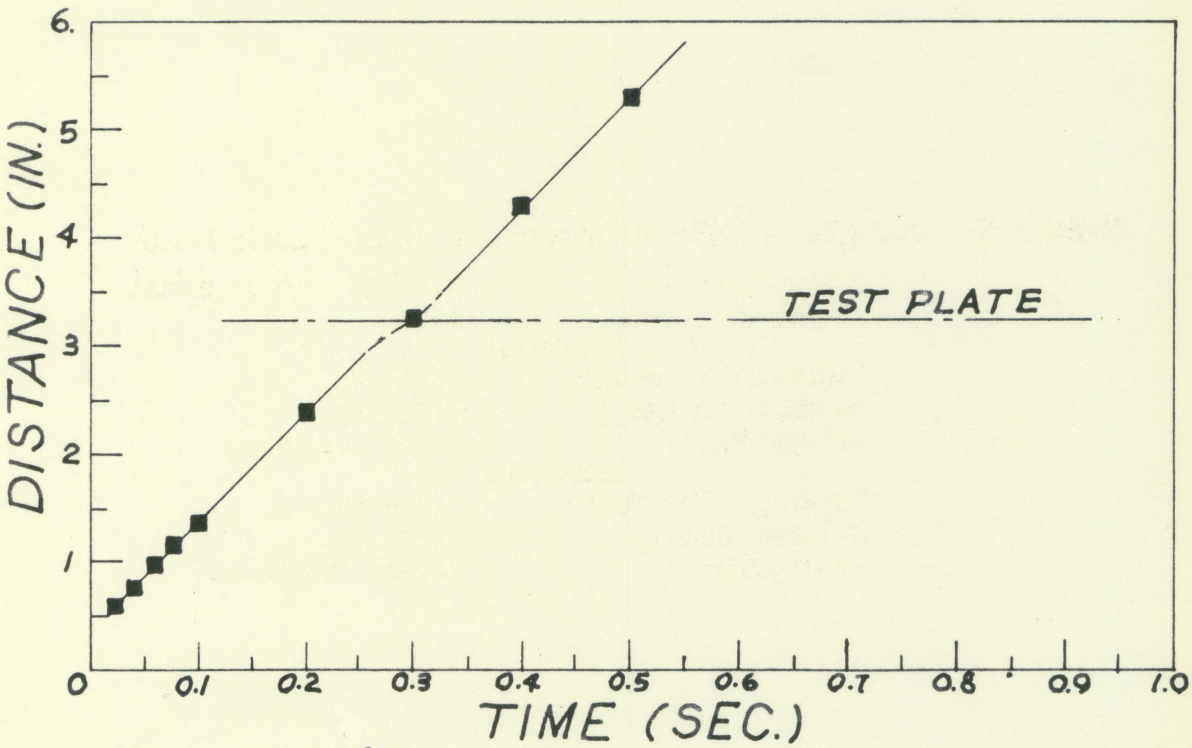
Film speed	0.0202 sec./frame.
Event No.	4
Incoming	
Bubble diameter	0.85 in.
Bubble height	0.25 in.
Velocity	0.825 ft./sec.
Outgoing	
Bubble diameter	0.75 in.
Bubble height	0.30 in.
Velocity	0.784 ft./sec.

Figure 5. Single bubble traverse of a 1/2 inch hole

Film speed	0.0203 sec./frame.
Event No.	14
Incoming	
Bubble diameter	0.85 in.
Bubble height	0.25 in.
Velocity	0.82 ft./sec.
Outgoing	
Bubble diameter	0.75 in.
Bubble height	0.30 in.
Velocity	0.836 ft./sec.



6
5
4
3
2
1
0
DISTANCE (IN.)
TEST PLATE
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
TIME (SEC.)



6.
5
4
3
2
1
0
DISTANCE (IN.)
TEST PLATE
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
TIME (SEC.)

noted that a small satellite bubble was formed as the incoming bubble passed through the plate and this bubble stayed very close to the main bubble. This small satellite bubble was not visible in the motion pictures. The small satellite then became entrained in the wake of the main bubble and rose at the same velocity with it.

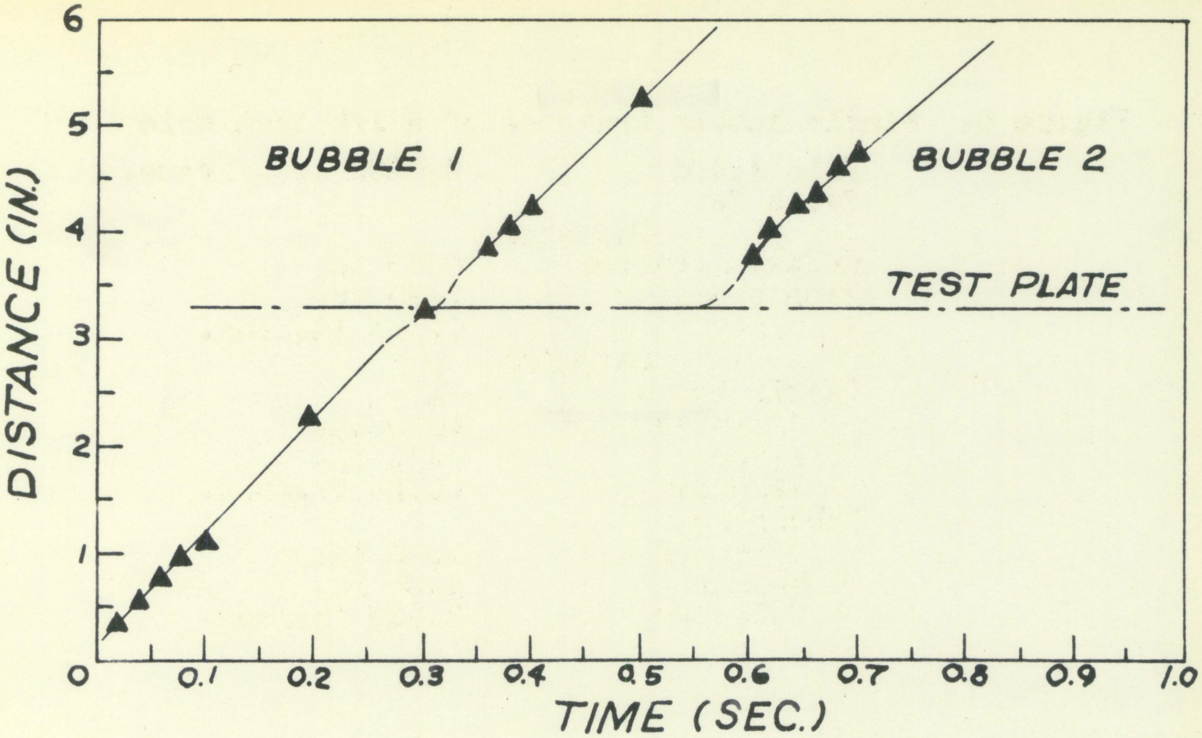
The 1/4 inch hole test showed a pronounced break up of the bubble. During the filming of bubble flow through this diameter hole 44 events were recorded. It may be seen from the data presented on the page facing Figure 6 that the incoming bubble broke into two almost equal bubbles. The breaking up of the bubble into two nearly equal bubbles was noted in 29 events, or 65.9% of the total events recorded. Both bubbles, upon leaving the plate, momentarily exceed the terminal velocity associated with the bubble. The phenomenon was noted by Datta _et al_. (2) but they could not offer an explanation. In viewing the films this momentary exceeding of the terminal velocity is due to the shape of the bubble upon leaving the plate. Since the coefficient of drag is dependent on the frontal area of an object, this was the most logical place to look. Upon leaving the plate the bubble is first elongated and then spherical in shape before assuming its ellipsoidal shape. Before assuming this ellipsoidal shape it assumes two shapes which would have smaller coefficient of drag. Since the bouyant force remains the same the bubble

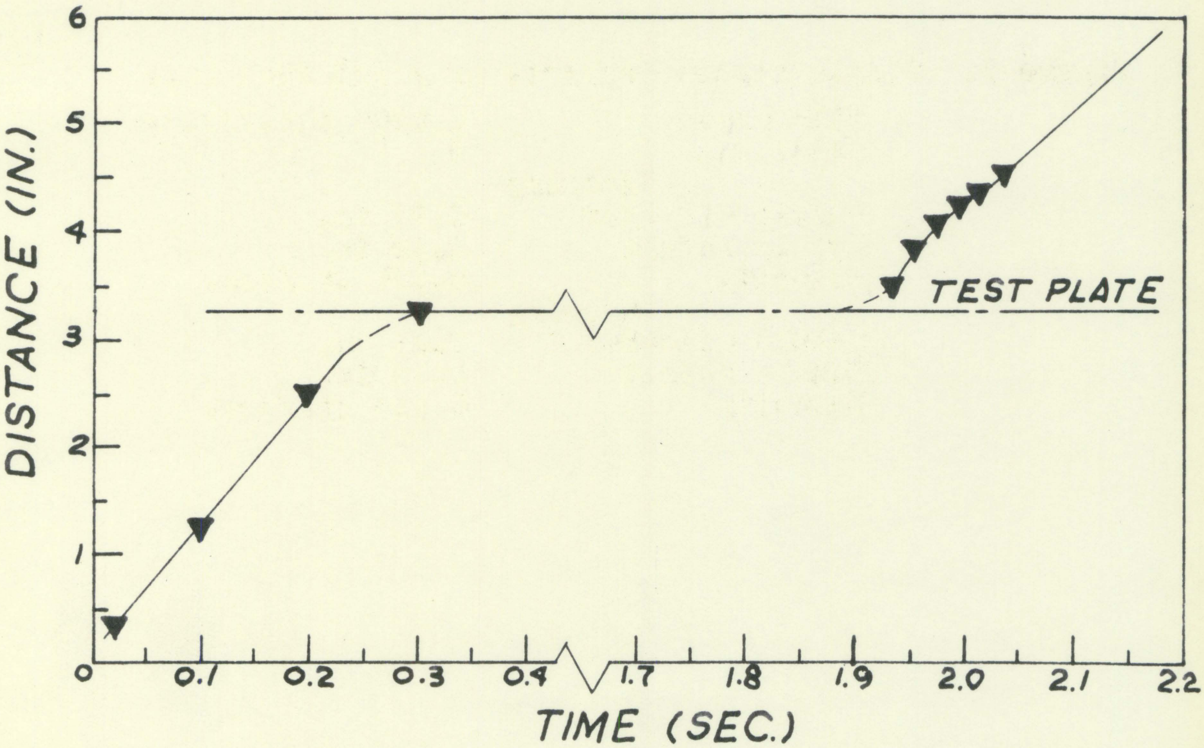
Figure 6. Single bubble traverse of a 1/4 inch hole

Film speed	0.0202 sec./frame.
Event No.	6
Incoming	
Bubble diameter	0.85 in.
Bubble height	0.20 in.
Velocity	0.825 ft./sec.
Outgoing	
Bubble No. 1	
Diameter	0.45 in.
Height	0.20 in.
Velocity	0.825 ft./sec.
Bubble No. 2	
Diameter	0.40 in.
Height	0.20 in.
Velocity	0.825 ft./sec.

Figure 7. Single bubble traverse of a 1/8 inch hole

Film speed	0.0204 sec./frame.
Event No.	8
Incoming	
Bubble diameter	0.75 in.
Bubble height	0.25 in.
Velocity	0.874 ft./sec.
Outgoing	
Bubble diameter	0.75 in.
Bubble height	0.25 in.
Velocity	0.614 ft./sec.


DISTANCE (IN.)
TIME (SEC.)
BUBBLE 1
BUBBLE 2
TEST PLATE
0
1
2
3
4
5
6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


DISTANCE (IN.)
TIME (SEC.)
TEST PLATE
0
1
2
3
4
5
6
0.1
0.2
0.3
0.4
1.7
1.8
1.9
2.0
2.1
2.2

passes through a "series" of terminal velocities which are associated with its shape. The final terminal velocity is dependent upon the stable shape of the bubble. Thus the exceeding of the stable terminal velocity is due to the elongated and spherical shapes of the bubble. The spacing between the emission of the two bubbles was found to vary between 0.4 to 0.6 seconds. During this time the second bubble would travel along the bottom of the plate until it came again to the hole. The retention of this second bubble was avoided by the conical shape of the test plate.

The 1/8 inch hole was very interesting in that the bubbles were stopped because of the small hole diameter. This was due to the surface tension force around the edge of the hole exceeding the bouyant force of the bubble. In 41 of the 47 events recorded the incoming bubble was stopped. The stopped bubble did not go through the hole until the bubble following it entered the chamber formed by the inlet plate and the test plate. As shown in Figure 7 upon passing through the plate the terminal velocity was again exceeded for the same reasons explained earlier. In this case, however, the bubble did not go through until it was initiated by a push from water displaced by the succeeding bubble. Again, as in the case of the 1/2 inch hole, the outgoing bubble is shown as only being one. Actually, it is composed of three or four small bubbles which were formed as the bubble "streamed" through the hole.

The dimensions shown for the outgoing bubble is for the group as a whole. This group has a smaller terminal velocity than the incoming bubble thus indicating the smaller size of its component bubbles.

Multiple Hole Test

In general, the flow pattern seen in each test was found to be the same. Small bits of colored paper were placed in the column so that the flow pattern could be seen. It was noted that the flow of air stayed in the center of the column while a thin layer of downward moving water existed along the walls of the tube. At higher flow rates the flow was characterized by great turbulence and churning in the central region of the cylinder caused by the appearance of large bubbles formed by the coalescence of smaller bubbles after leaving the test plate. The large bubbles at times broke so violently at the interface that water was expelled from the tube. When this occurred the test was terminated since it would be impossible to maintain the interface level at the same height.

Due to the ability of the air to hold up the air-water column on the upper side of the test plate, the chamber formed by the inlet plate and test plate had a tendency to become voided of water. This tendency increased as the diameter of the holes was decreased, so that the chamber became completely voided at the highest flow rate recorded during the 1/4 inch hole test. In reference to Figure 3 it will be noted that a half voiding of this volume would expose the manometer tap.

Because of the turbulence and instability associated with bubbling, one finds that bubbling does not occur from all holes at the same time. This happened during all tests, but it was not possible at the time to estimate the total number of effective holes at a given time. Based on observations at the time of the test, it is suspected that approximately one-half to three-quarters of the total number of holes pass air at any given instant.

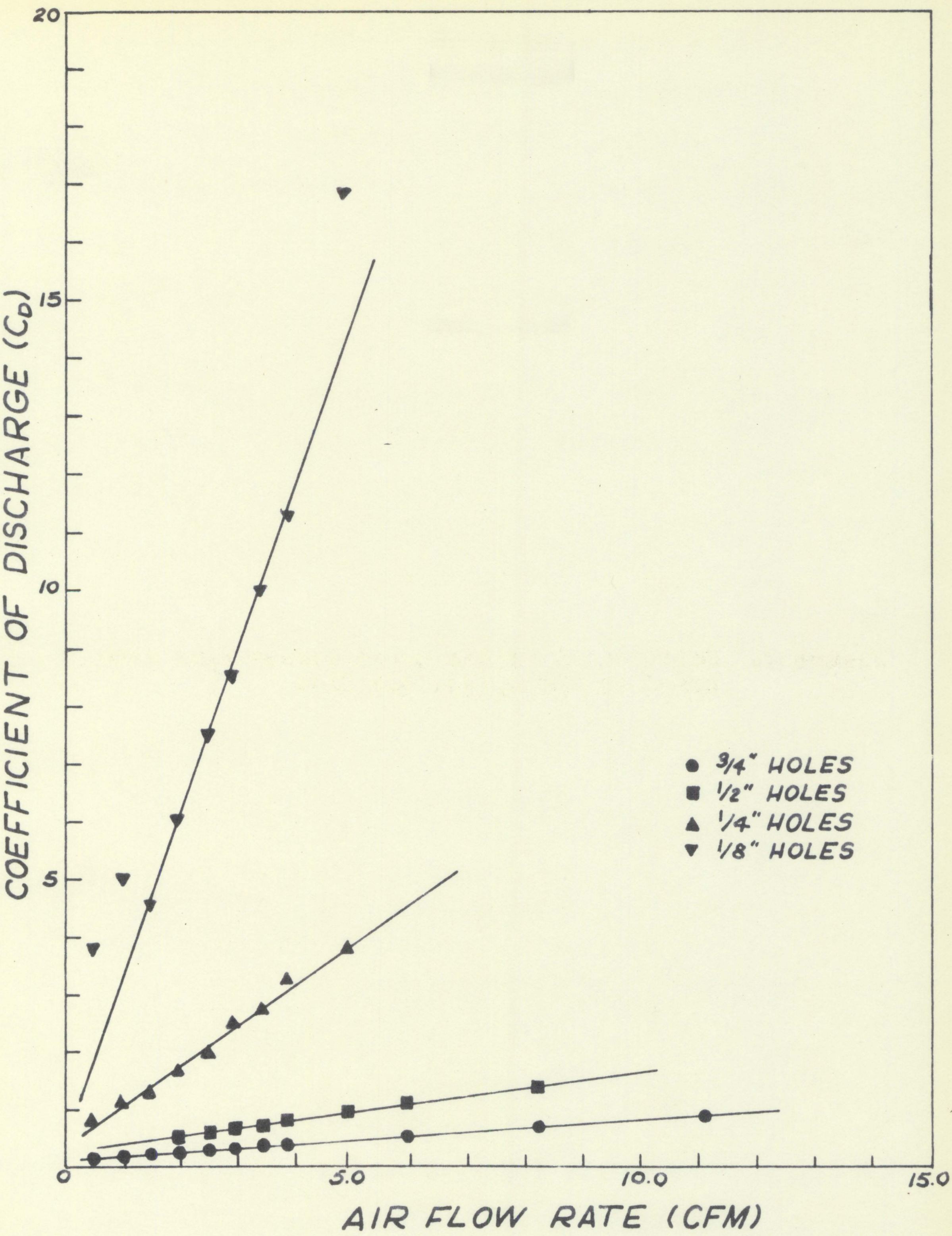
The calculation of the coefficient of discharge through the plates was made by assuming incompressible flow and then compressible flow of the air through the test plates. All original data for this portion will be found in Appendix B.

Calculation of the coefficient of discharge, C_D, for incompressible flow was based on the equation

$$C_D = \frac{Q}{a_o \sqrt{2gh}} \qquad (5)$$

where
C_D = the coefficient of discharge
Q = actual flow rate, CFS
a_o = total area of holes, $ft.^2$
g = gravitational constant, 32.17 $ft./sec.^2$
h = pressure drop across plate, $ft._{H_2O}$

Figure 8. Coefficient of discharge versus flow rate based on incompressible flow


20
15
10
5
0
5.0
10.0
15.0
COEFFICIENT OF DISCHARGE (C_D)
AIR FLOW RATE (CFM)
3/4" HOLES
1/2" HOLES
1/4" HOLES
1/8" HOLES

With this equation the graph shown in Figure 8 was found. In each case a linear relationship exists between the coefficient of discharge and the air flow rate. Since the fluid involved is compressible, the coefficients were found to exceed unity for 1/2, 1/4 and 1/8 inch holes. This is due to the fact that energy losses due to expansion are not considered.

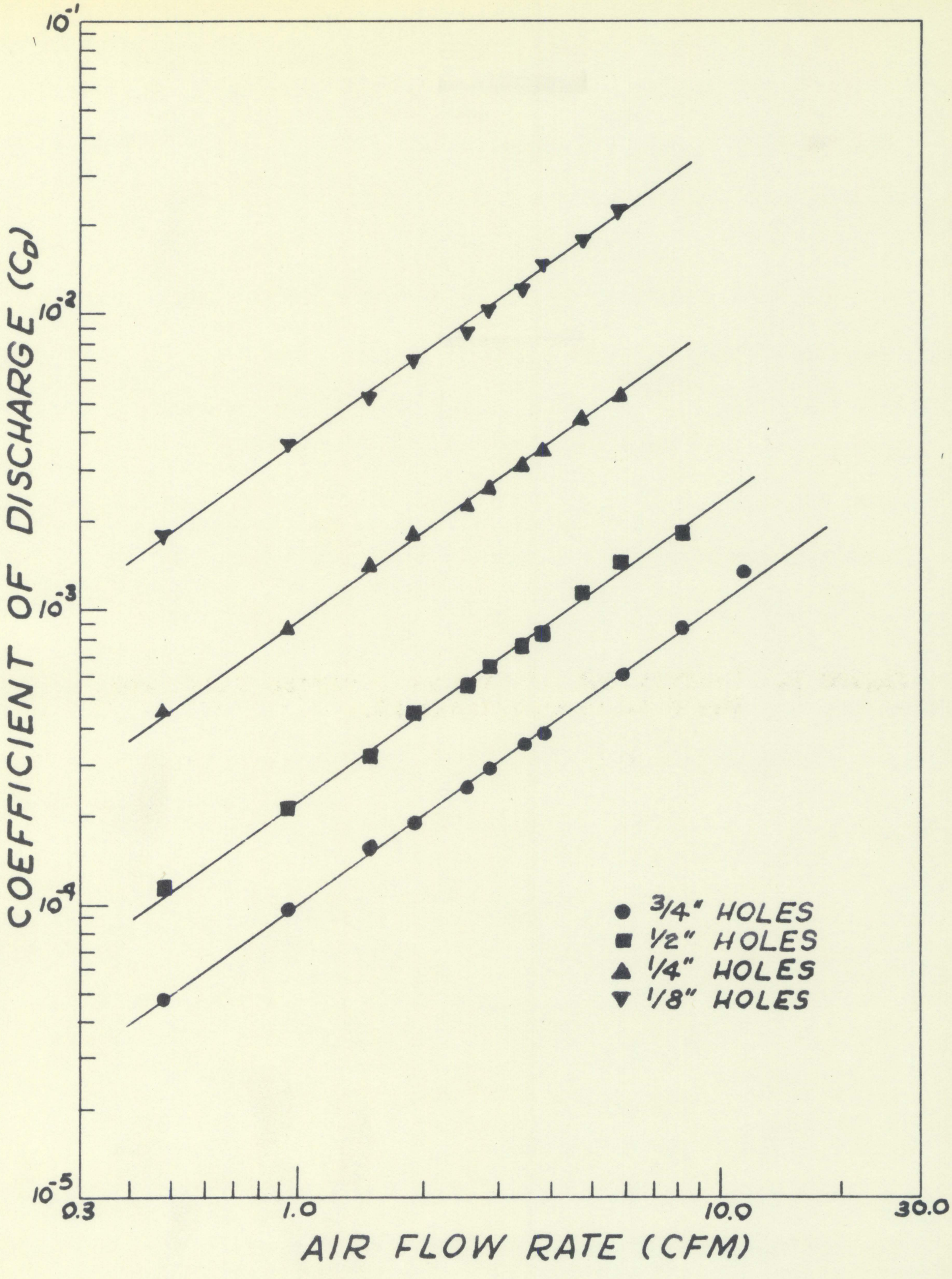
For the calculation of the coefficient of discharge based on compressible flow, the following equation given by Leibson *et al*. (10) was used

$$C_D = \frac{\omega}{a_o P_1 \sqrt{\frac{gKM_W}{RT_1}\left(\frac{2}{K+1}\right)^{\frac{K+1}{K-1}}}} \qquad (6)$$

where
- C_D = coefficient of discharge
- ω = mass flow rate of air, $lb._m$/sec.
- a_o = total area of holes, $ft.^2$
- P_1 = absolute pressure upstream from orifice, $lb._f/ft.^2$
- g = gravitational constant, 32.17 $ft./sec.^2$
- K = ratio of constant pressure to constant volume specific heats of air
- M_W = molecular weight of air, lb./lb. mole
- T_1 = absolute temperature of air upstream, ^oR
- R = gas constant

A logarithmic plot of the coefficient of discharge utilizing this equation is shown in Figure 9. Again linear plots were

Figure 9. Coefficient of discharge versus flow rate based on compressable flow



COEFFICIENT OF DISCHARGE (C_D)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.3
1.0
10.0
30.0
AIR FLOW RATE (CFM)
● 3/4" HOLES
■ 1/2" HOLES
▲ 1/4" HOLES
▼ 1/8" HOLES

obtained and, in this case, the upward displacement of each line is an indication of the increase in slope, on a rectangular plot, as the holes became smaller. The values here, however, do not exceed unity because an allowance has been made for energy loss due to expansion. Although the pressure ratio before and after the test plate in this study was near unity, it should be noted that the linearity will disappear as the critical pressure rates for air is approached.

The values of the coefficients of discharge are probably lower than the true values because the area of flow in each case was considered to be the area of all 16 holes. As was mentioned earlier the flow actually occurred through less than all of the holes in the plate.

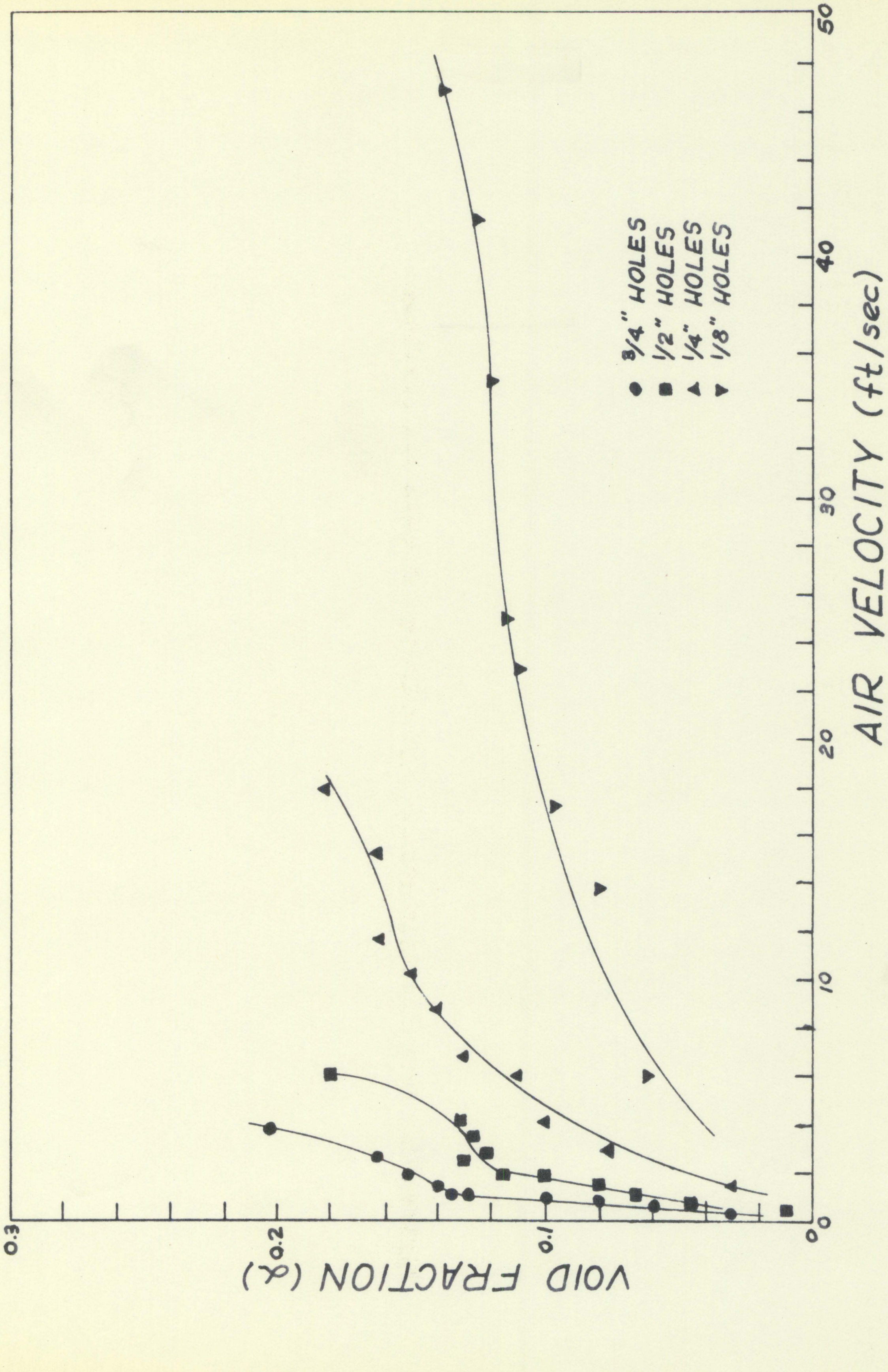
If the liquid in the manometer is water and the manometer fluid has a specific gravity of 2.95, the void fraction, α, is found by using the equation

$$\alpha = \frac{122h}{z_2(\gamma_L - \gamma_g)} \qquad (7)$$

where
- α = void fraction
- γ_g = density of air, lb./ft.^{3}
- γ_L = density of water, lb./ft.^{3}
- z_2 = distance between manometer taps, ft.
- h = pressure drop, ft.$_{H_2O}$

The derivation of this equation is given in Appendix A. In Figure 10 the void fraction is plotted as a function of the

Figure 10. Void fraction versus air velocity through the orifices

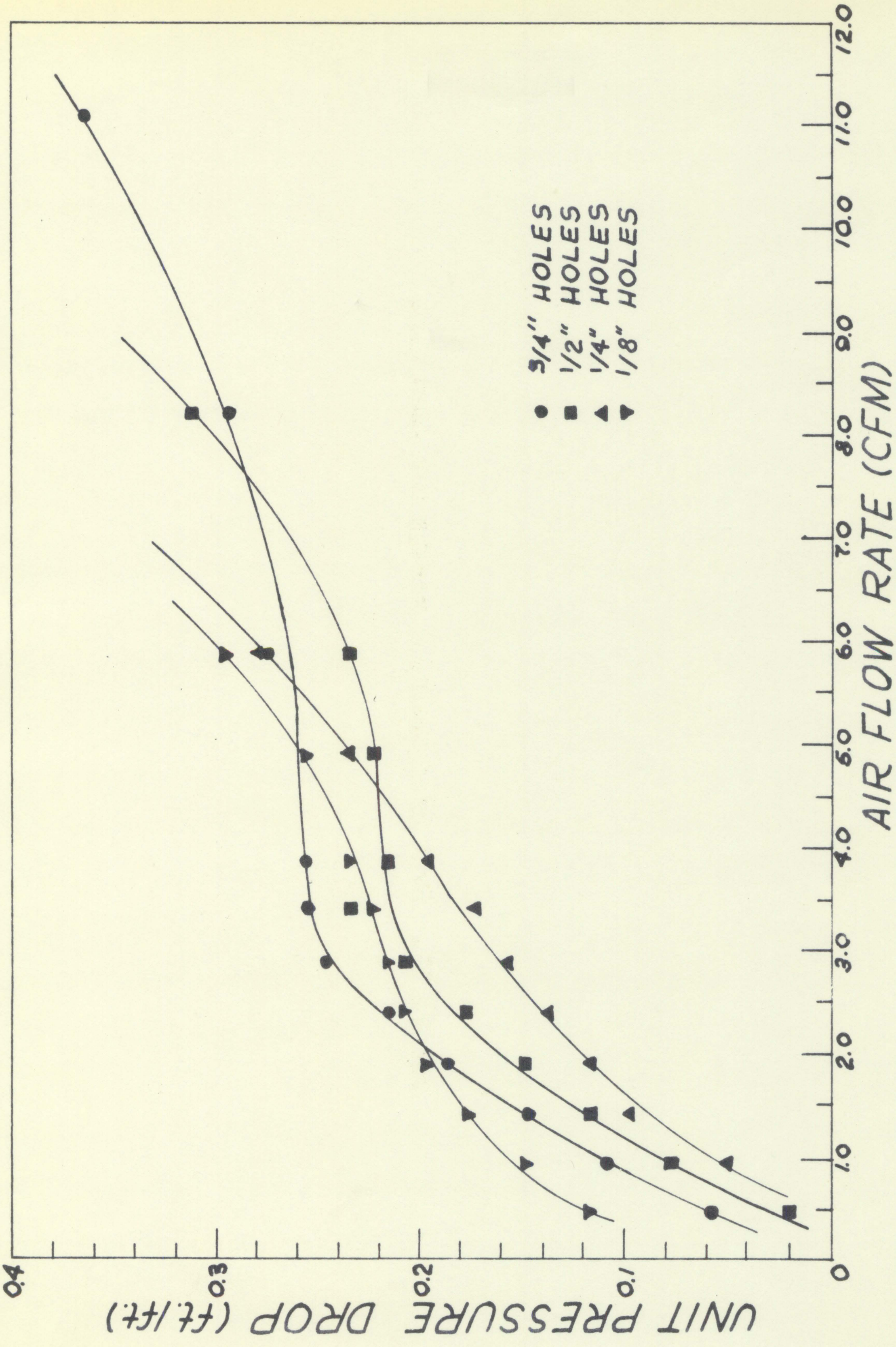

VOID FRACTION (α)
0.3
0.2
0.1
0
0
10
20
30
40
50
AIR VELOCITY (ft/sec)
● 3/4" HOLES
■ 1/2" HOLES
▲ 1/4" HOLES
▼ 1/8" HOLES

apparent air velocity through the plate, in order to spread out the curves so that they can be seen more easily. It will be noted that there appears to be a transition when the void fraction is between 0.1 to 0.2. More will be said about this in the discussion of the following results.

Govier et al. (6) experimented with air-water systems and found a transition zone from bubble to slug flow when the unit pressure drop was approximately 0.2 $ft._{H_2O}/ft.$ What happens is that at low gas flow rates the gas is dispersed as discrete bubbles which increase in number and size as the flow is increased. When the flow rate has reached a certain point the bubbles begin to coalesce into larger "bullet shaped" bubbles. These slugs then grow in diameter and length. This is precisely the type of flow that was observed in the experiments.

The unit pressure drop is plotted as a function of the air flow rate in Figure 11. It is easily seen that a definite transition does exist in the region of 0.2 $ft._{H_2O}/ft.$ unit pressure drop for the 3/4 inch holes and exists over the air flow rate range 3.0 to 8.0 CFM. This plot shows the effect which a perforated plate has upon the flow above it. It can be seen from the figure that as the hole size is reduced, the range of the transition is shorter and begins at a lower unit pressure drop. There is a steady reduction for plates with 3/4, 1/2 and 1/4 inch holes but a deviation for the plate with

Figure 11. Unit pressure drop versus air flow rate

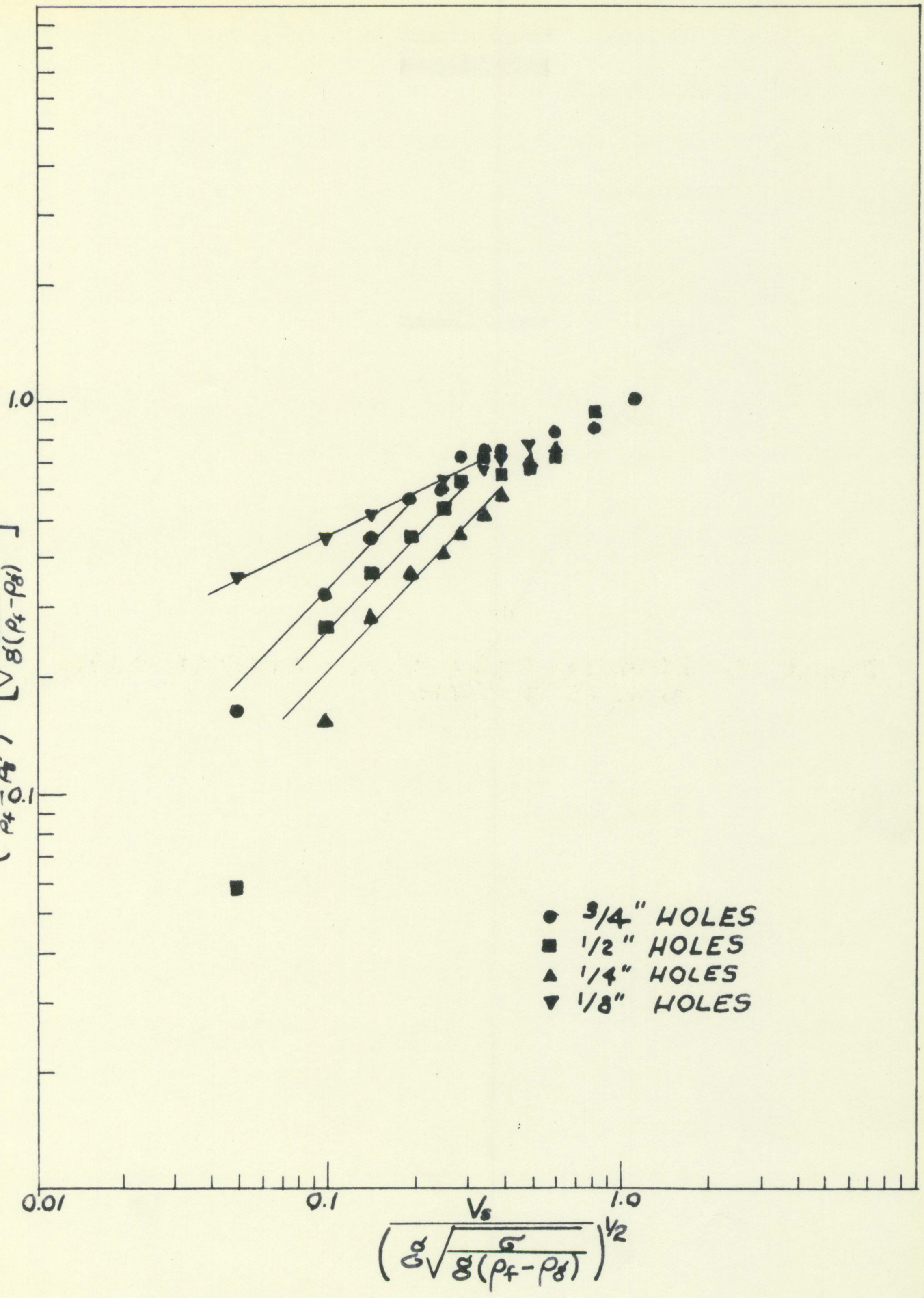

● 3/4" HOLES
■ 1/2" HOLES
▲ 1/4" HOLES
▼ 1/8" HOLES
AIR FLOW RATE (CFM)
UNIT PRESSURE DROP (ft/ft)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
0.1
0.2
0.3
0.4

1/8 inch holes. At low flow rates the unit pressure drop is greater for the 1/8 inch holes. This may be due to a concentration of bubbles in the center of the column. The transition begins at a lower flow rate but then ends before that of the 1/4 inch holes.

The shape of each of these curves is characterized by three regions. The first is the bubble flow region, the second the transition region and the third is the slug flow region. The slope of the curve in the slug flow region is less than that for the bubble region, thus indicating that the unit pressure drop (and void fraction) does not increase as fast when the flow rate increases. This occurs because of the coalescence of the smaller bubbles into larger bubbles.

Figure 12 is a plot of the dimensionless equation developed by Sterman (14) and modified by Wilson <u>et al</u>. (19) which was given earlier as Equation 4. Surface tension values were calculated by use of a formula given by Gambill (5). The values for the 3/4, 1/2 and 1/4 inch plates were found to parallel each other so that the exponential "a" was found to be 0.708, while the constant, K, was found to be 1.725, 1.43 and 1.145 for the 3/4, 1/2 and 1/4 inch holes respectively. For the 1/8 inch plate "a" equals 0.398 while K is 1.135. Wilson (19) found, for the range under consideration, that "a" equals 0.62 and K equals 0.68. The K factor in each case is a measure of the change in the slope

Figure 12. Dimensional plot of data according to the equation by Wilson


1.0
0.1
0.01
0.1
1.0
$\frac{\alpha}{\left(\frac{\rho_f}{\rho_f - \rho_g}\right)^{0.17}} \left[\frac{d}{\sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}}}\right]^{0.1}$
$\left(\frac{V_s}{g\sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}}}\right)^{1/2}$
3/4" HOLES
1/2" HOLES
1/4" HOLES
1/8" HOLES

on a rectangular plot. Although the exponential "a" compares favorably with Wilson for the 3/4, 1/2 and 1/4 inch holed plates the factor K is much higher. This may be attributable to the differences between a two-phase one component system, such as steam-water, and a two-phase two component system, such as air-water. The change in the value of "a" and K associated with the 1/8 inch plate is most likely due to the change in flow regimes noted earlier. The change in the value of K for the 3/4, 1/2 and 1/4 inch holed plate is possibly due to the transition occuring at lower unit pressure drops which also affects the void fraction.

DISCUSSION AND CONCLUSIONS

The results of the single-hole, single-bubble study suggest that there is a relationship between hole diameter and bubble break up. Since only bubbles in the range of 0.70 to 0.85 inches in diameter were used, it may be concluded that the amount of break up is due to the difference in the diameters of the hole and incoming bubble. As the hole size was reduced the incoming bubble was broken up into smaller and smaller segments. When the surface tension force around the edge of the hole exceeded that of bouyancy, the bubble was stopped, as in the case of the 1/8 inch hole. The number of bubbles increased to a maximum of about four for the 1/8 inch plate. Thus the number of bubbles was increased and their size decreased.

The coefficients of discharge for both compressible and incompressible flow were found to be linear functions of the air flow rate. In each case the intercept was zero thus giving a coefficient of discharge of zero for no flow rate. The coefficients were found to increase with increasing flow rate and decreasing hole size, which would be expected as the actual flow rate approached the ideal flow rate.

The void fraction in the column above the test plate varies as the type of flow is varied. A transition was found which could be described as being a change from bubble flow to slug flow. This was verified by comparing the unit pressure drop in the column to the results of another investigator who found the same transition. The transition occurs at approximately 0.2 ft.$_{H_2O}$/ft. unit pressure drop which corresponds to a void fraction of about 0.14. The range of flow rate over which the transition occurs is reduced as the hole size of the test plate is reduced. There is also a slight lowering of the unit pressure drop at which the transition begins as the hole size is decreased.

Comparison of the air-water system with the steam-water system was favorable in that the exponential "a", given in Equation 4, was found to agree with that found by Wilson et al. (19) (20) and Sterman (14) so that there was agreement on this point. However, the constant, K, was quite different and it is possible that this is due to the difference in the surface tension and gas and liquid densities between two-phase one component systems and two-phase two component systems. The deviation of the 1/8 inch holed plate cannot be readily explained unless it is due to the fact that the smaller bubbles produced at the lower flow rates cause a much higher void fraction to be measured in the center of the column. The possibility that there was an extreme amount of experimental error at these low flow rates can be discounted somewhat by the fact that the results of the coefficients of discharge were good and the manometers used to determine the pressure drop across the plate and in the column were coupled in the same system as shown in Figure 1.

From these results it may then be concluded that perforated plates do have an effect on bubble flow in a column. They have a definite effect upon the type of flow present in the column in so far as the transition from bubble flow to slug flow is concerned. The results of the single-hole, single-bubble study suggest that as the holes become smaller the bubbles formed are smaller, which would cause smaller bubbles to be present at the interface, thus producing less carryover as explained by Wilson and Grenda (18). The comparison of air-water to steam-water systems is good but there appears to be an inherent difference between one and two component systems because of differences in surface tension, gas density and liquid densities.

SUGGESTED TOPICS FOR FURTHER INVESTIGATION

The results of this study suggest further experiments which may be done to add to the knowledge of bubble flow through a perforated plate.

Further studies on the flow of single bubbles through an orifice should be conducted, not only to provide further experimental information, but to possibly develop a theory of bubble break up similar to that found for static and dynamic bubble formation at an orifice.

In the area of the effect of a perforated plate on bubble flow many more points can be investigated. The wall effect should be studied, although there did not seem to be a significant effect between the results of Govier *et al*. (6) and this experiment as far as the correlation between unit pressure drop and the bubble to slug flow transition is concerned. Studies of hole shape and array may be conducted as well. The most important investigation would be to see if these, or similar, results can be found in steam-water systems operating at the higher pressures found in boiling nuclear reactors. The transition noted by Wilson *et al*. (19) (20) suggests that this might be so.

LITERATURE CITED

1. Brown, R. S. Bubbling from perforated plates. U. S. Atomic Energy Commission Report UCRL-8558 [California. Univ., Berkeley. Ratiation Lab.]. 1958.

2. Datta, R. L., Napier, D. H. and Newitt, D. M. The properties and behavior or gas bubbles formed at a circular orifice. Institution of Chemical Engineers Transactions (Great Britain) 28: 14-26. 1950.

3. Davidson, L. A study of the formation of gas bubbles from horizontal circular submerged orifices. Microfilm copy 3678. Unpublished Ph. D. thesis. Columbia University, New York, N. Y. Ann Arbor, Michigan, University Microfilms. 1951.

4. Davidson, L. and Amick, E. H. Formation of gas bubbles at horizontal orifices. Journal American Institute of Chemical Engineers 2: 337-342. 1956.

5. Gambill, W. R. Surface tension for pure liquids. Chemical Engineering 65, No. 7: 146-150. April 7, 1958.

6. Govier, G. W., Radford, B. A. and Dunn, J. S. C. The upwards vertical flow of air-water mixtures. Canadian Journal of Chemical Engineering 35: 58-70. 1957.

7. Haberman, W. L. and Morton, R. K. An experimental investigation of the drag and shape of air bubbles rising in various liquids. U. S. Atomic Energy Commission Report TMB-802 [David W. Taylor Model Basin, Carderock, Md.]. 1953.

8. Hughes, R. R., Hardlos, A. E., Evans, H. D. and Maycock, R. L. Formation of bubbles at simple orifices. Chemical Engineering Progress 51: 557-563. 1955.

9. Hunt, C. d'A. Capacity factors in the performance of perforated plate columns. U. S. Atomic Energy Commission Report UCRL-2696 [California. Univ., Berkeley. Radiation Lab.]. 1954.

10. Leibson, I., Holcomb, E. G., Cacaso, A. G. and Jacomic, J. J. Rate of flow and mechanics of bubble formation from single submerged orifices. Journal American Institute of Chemical Engineers 2: 296-306. 1956.

11. Peebles, F. N. and Garber, H. J. Studies on the motion of gas bubbles in liquids. Chemical Engineering Progress 49: 88-97. 1953.

12. Petrick, M. Two-phase air-water flow phenomena. U. S. Atomic Energy Commission Report ANL-5787 [Argonne National Lab., Lemont, Ill.]. 1958.

13. Rosenberg, B. The drag and shape of bubbles moving in liquids. U. S. Atomic Energy Commission Report TMB-727 [David W. Taylor Model Basin, Carderock, Md.]. 1950.

14. Sterman, L. S. The generalization of experimental data concerning the bubbling of vapor through liquid. Soviet Physics--Technical Physics 7: 1479-1485. 1957.

15. Uno, S. and Kintner, R. C. Effect of wall proximity on rate of rise of single air bubbles in quiescent liquid. Journal American Institute of Chemical Engineers 2: 420-425. 1956.

16. Van Krevelen, D. W. and Hoftijger, P. J. Studies of gas bubble formation. Chemical Engineering Progress 46: 29-35. 1950.

17. Verschoor, H. Some aspects of the motion of a swarm of gas bubbles rising through a vertical liquid column. Institution of Chemical Engineers Transactions (Great Britain) 28: 52-57. 1950.

18. Wilson, J. J., Grenda, R. J. Moisture control in nuclear superheating. Power 106, No. 2: 70-72. Feb., 1962.

19. Wilson, J. F., Grenda, R. J. and Patterson, J. F. Steam volume fraction in a bubbling two-phase mixture. American Nuclear Society Transactions 4: 356-357. 1961.

20. Wilson, J. F., Grenda, R. J. and Patterson, J. F. Velocity of rising steam in a bubbling two-phase mixture. American Nuclear Society Transactions 5: 151-152. 1962.

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Sincere gratitude is also expressed to Dr. Glenn Murphy, Head of the Department of Nuclear Engineering at Iowa State University, for his aid in the presentation of results and writing of this thesis.

APPENDIX A

Derivation of Equation 7

Referring to Figure 13, one may derive the void fraction formula in the following manner

$$h_1\gamma_L + (z_1-h_1)\gamma_o = h\gamma_M + (h_2-h)\gamma_2 + (h_1-h_2)\gamma_v$$

$$+ (z_1-h_1)\gamma_o$$

$$h_1\gamma_L = h\gamma_M + h_2\gamma_L - h\gamma_L + h_1\gamma_v - h_2\gamma_v$$

$$\gamma_v = \gamma_L + \frac{h(\gamma_L-\gamma_M)}{z_2}$$

but

$$\gamma_v = \alpha\gamma_g + (1-\alpha)\gamma_L$$

where

α = void fraction

$$\gamma_L + \frac{h(\gamma_L-\gamma_M)}{z_2} = \alpha\gamma_g + \gamma_L - \alpha\gamma_L$$

$$\alpha = -\frac{h(\gamma_L-\gamma_M)}{z_2(\gamma_L-\gamma_g)}$$

If $\gamma_M = 2.95\,\gamma_L$, $\gamma_L = 62.4$ lb./ft.^{3}

then

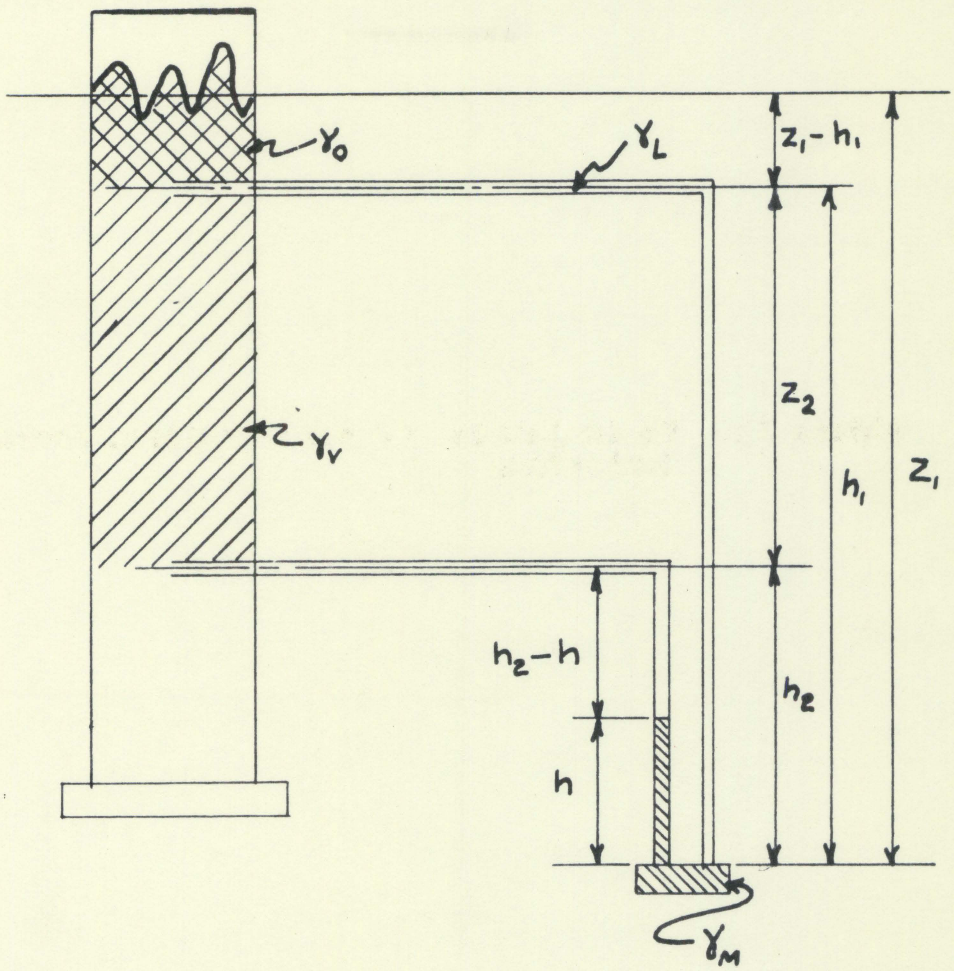
$$\alpha = \frac{122h}{z_2(\gamma_L - \gamma_g)}$$

where α = void fraction

h = pressure drop, $ft._{H_2O}$

z_2 = distance between manometer taps, ft.

Figure 13. Nomenclature for void fraction formula derivation


γ_0
γ_L
$z_1 - h_1$
γ_v
z_2
h_1
z_1
$h_2 - h$
h_2
h
γ_M

APPENDIX B

Data for Multiple Hole Tests

Table 2. 16 - 3/4 inch holes

Run No.	Inclinometer Reading (in.)	Q (CFM)	Air Temp. (°F)	Air Press. (psig)	Water Temp. (°F)	h (in.)	P (in.)
1	0.05	0.43	70	1.6	64	0.3	0.32
2	0.10	0.86	70	1.70	64	0.55	0.40
3	0.15	1.29	70	1.50	64	0.75	0.55
4	0.20	1.72	70	1.65	64	0.95	0.70
5	0.25	2.15	70	1.70	64	1.10	0.80
6	0.30	2.58	70	1.70	64	1.25	0.90
7	0.35	3.05	70	1.75	64	1.30	1.00
8	0.40	3.44	70	1.75	64	1.30	1.05
9	0.60	5.15	70	2.20	64	1.40	1.25
10	0.80	6.88	70	2.80	64	1.50	1.40
11	1.00	8.56	70	4.20	64	1.85	1.55

Table 3. 16 - 1/2 inch holes

Run No.	Inclinometer Reading (in.)	Q (CFM)	Air Temp. (°F)	Air Press. (psig)	Water Temp. (°F)	h (in.)	P[a] (in.)
1	0.05	0.43	72	1.7	63	0.10	0.45
2	0.10	0.86	72	1.7	63	0.40	0.55
3	0.15	1.29	72	1.7	63	0.60	0.70
4	0.20	1.72	72	1.7	63	0.75	0.85
5	0.25	2.15	72	1.7	63	0.90	1.00
6	0.30	2.58	72	1.7	63	1.05	1.05
7	0.35	3.05	72	1.7	63	1.20	1.15
8	0.40	3.44	72	1.75	63	1.10	1.25
9	0.50	4.35	72	2.00	63	1.15	1.40
10	0.60	5.15	72	2.20	63	1.20	1.55
11	0.80	6.88	72	2.90	63	1.60	1.70

[a] Zero setting = 0.2 in.

Table 4. 16 - 1/4 inch holes

Run No.	Inclinometer Reading (in.)	Q (CFM)	Air Temp. (°F)	Air Press. (psig)	Water Temp. (°F)	h[a] (in.)	P[b] (in.)
1	0.05	0.43	72	1.7	64	0.1	0.35
2	0.10	0.86	72	1.7	64	0.35	0.60
3	0.15	1.29	72	1.7	64	0.60	0.85
4	0.20	1.72	72	1.7	64	0.70	0.90
5	0.25	2.15	72	1.7	64	0.80	1.05
6	0.30	2.58	72	1.7	64	0.90	1.15
7	0.35	3.05	72	1.7	64	1.00	1.25
8	0.40	3.44	72	1.7	64	1.10	1.30
9	0.50	4.35	72	1.8	64	1.30	1.35
10	0.60	5.15	72	2.2	64	1.40	1.50

[a] Zero setting = -0.1 in.

[b] Zero setting = 0.1 in.

Table 5. 16 - 1/8 inch holes

Run No.	Inclinometer Reading (in.)	Q (CFM)	Air Temp. (°F)	Air Press. (psig)	Water Temp. (°F)	h (in.)	P[a] (in.)
1	0.05	0.43	72	1.7	62	0.60	0.25
2	0.10	0.86	72	1.7	62	0.75	0.45
3	0.15	1.29	72	1.7	62	0.90	1.00
4	0.20	1.72	72	1.7	62	1.00	1.05
5	0.25	2.15	72	1.7	62	1.05	1.10
6	0.30	2.58	72	1.75	62	1.10	1.15
7	0.35	3.05	72	1.80	62	1.15	1.20
8	0.40	3.44	72	1.80	62	1.20	1.20
9	0.50	4.35	72	2.0	62	1.30	0.90
10	0.60	5.15	72	2.2	62	1.50	0.75

[a] Zero setting = 0.1 in.