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HYDRAULIC GRADIENT

AND

PRESSURE DROP ON A PERFORATED PLATE

by

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Department Committee on
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ABSTRACT

HYDRAULIC GRADIENT AND PRESSURE DROP ON A PERFORATED PLATE

By: Robert T. Hucks, Jr.
William P. Thomson

Submitted for the degree of Master of Science in the Department of Chemical Engineering at the Massachusetts Institute of Technology on August 24, 1951.

Hydraulic gradient and pressure drop on a perforated plate were studied using a 120" x 13 1/2" test section of 14 gauge sheet steel. A 60" x 10" section of the plate was perforated with 1/8" holes on 1/4" equilateral triangular centers, the long dimension being parallel to liquid flow. The inlet and outlet calming sections were each 24" long.

All data were taken using an air-water system. The superficial air velocity was varied from 5.7 to 7 ft. per sec.; water rate was varied from 0 to 24 gpm/ft.; and weir height was varied from 1/4 to 1".

Hydraulic gradient data were correlated using a Fanning-type friction expression:

$$F = \frac{f' \, V_f^2 \, N}{2g_c \, r_h}$$

Where f' was correlated against Re':

$$Re' = \frac{r_h \, V_f \, \rho_f}{\mu_f}$$

The pressure drop data were correlated using the following expression for the drop through the perforations:

$$h_o = CV_p^2$$

The total plate pressure drop was found to consist of this drop, a loss due to surface tension effects, and a loss equivalent to the hydrostatic head of the liquid above the perforations.

Methods were developed for predicting the hydraulic gradient and pressure drop on a perforated plate operating in the range of variables studied.

Thesis Supervisor: E. R. Gilliland
Title: Professor of Chemical Engineering

Chemical Engineering Department
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
August 23, 1951

Professor Joseph S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Sir:

In accordance with the regulations of the Faculty, this thesis, entitled "Hydraulic Gradient and Pressure Drop on a Perforated Plate," is hereby submitted in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering.

Respectfully submitted.

Robert T. Hucks, Jr.

William P. Thomson

ACKNOWLEDGMENT

The authors wish to express their appreciation to Professor E. R. Gilliland for his many helpful suggestions in supervising this thesis.

Credit is also due to Mr. H. H. Carter and the Chemical Engineering Shop under the direction of Mr. H. C. Chasen for their cooperation.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

INDEX OF FIGURES

INDEX OF TABLES

I SUMMARY

The successful operation of a perforated plate depends to a large extent on the hydraulic gradient of liquid on the plate and the pressure drop of the vapor in passing through the plate. At the present time, little information is available in the literature concerning these phenomena and no satisfactory method for predicting them has been proposed. The purpose of this thesis is to develop a practical method of predicting the pressure drop and hydraulic gradient on a perforated plate.

Data were taken using an air-water system and a perforated plate having 1/8-inch perforations on 1/4-inch equilateral triangular centers. The range of operating conditions studied involved liquid rates up to 24 gpm/ft., vapor superficial velocities up to 7 ft./sec., and seals up to 2 inches. This range was considered compatible with present day commercial practice in designing towers. Data were also taken using the plate with no liquid on it.

The following conclusions for hydraulic gradient and pressure drop on a perforated plate were drawn from the data of this investigation:

1. The hydraulic gradient increases with increasing liquid flow rate.

2. The hydraulic gradient increases with decreasing exit weir height.

3. The hydraulic gradient may be predicted by use of a Fanning-type friction expression.

4. The hydraulic gradient on a perforated plate is about 17% of that on a bubble-cap plate operating at the same liquid rate per unit of plate width and the same exit weir height.

5. The pressure drop through the perforations for both a dry plate and wet plate is a function of the square of the vapor velocity.

6. The total plate pressure drop increases with increasing vapor velocity.

7. The total plate pressure drop increases with increasing liquid rate.

8. The total plate pressure drop increases with increasing exit weir height.

9. Knowing the vapor velocity through the perforations, weir height, and liquid flow rate, the total plate pressure drop may be calculated by use of the equation:

$$h_{\pi} = h_o + h_t + 0.46\ h_c$$

10. The total plate pressure drop on a perforated plate is about 92% of that on a bubble-cap plate operating at the same vapor rate per unit area of plate, the same liquid rate per unit of plate width, and the same liquid level on the plate. If the same comparison is made with the plates operating at equal seals (liquid level on the perforated plate equal to the height of liquid above cap slots of the bubble-cap plate), the perforated plate drop is about 68% of that on the bubble-cap plate.

The hydraulic gradient data were correlated very well by the use of a Fanning-type friction expression:

$$F = \frac{f'\ V_f^2\ N}{2g_c\ r_h}$$

Where f' was correlated against Re':

$$Re' = \frac{r_h\ V_f\ \rho_f}{\mu_f}$$

This correlation was used to develop a method for predicting hydraulic gradient on a perforated plate which depends only upon the exit weir height and the liquid rate.

The plate pressure drop on a perforated plate was correlated with the expression:

$$h_o = CV_p^2$$

With a perfectly dry plate, the constant was found to be 0.00029. However, with liquid on the plate, the pressure drop through the perforations was greater than predicted using this constant, and the constant 0.00047 was found to apply. The higher pressure drop was believed to be a result of regions of inactive perforations present during stable runs. The total plate pressure drop was found to consist of the above-mentioned drop through the perforations, a loss due to surface tension effects, and a loss equivalent to the hydrostatic head of the liquid above the perforations. A procedure was developed for predicting the total plate pressure drop on a perforated plate in the range of variables studied. This procedure depends only upon the vapor rate, liquid rate, and exit weir height.

II INTRODUCTION

A. Object of the Investigation

This thesis has two main objectives:

1. To develop a simple method of predicting pressure drop on a perforated plate.

2. To present a practical method of predicting hydraulic gradient on a perforated plate.

At the present time perforated plates are used to a limited extent in fractionating columns as a means for promoting vapor-liquid contact. Their simplicity of construction makes the cost of both fabrication and maintenance low in comparison to that of the commonly employed bubble-cap plates. They have proven effective for liquids containing suspended solids, such as the beer mashes in alcohol production, which tend to clog bubble-caps.

The chief objection to the use of perforated plates is their tendency to "dump" or "prime" more easily than bubble-cap plates so that they operate satisfactorily within a narrower range of vapor and liquid rates.

The successful operation of a perforated plate depends to a large extent on the pressure drop of the vapor in passing through the plate and on the hydraulic gradient of the liquid passing over the plate. As the vapor flow rate in a column is increased, the pressure drop per plate increases until it reaches the point where liquid can no longer flow down the downpipes and may even begin to flow upward, resulting in "priming." As the liquid flow rate is increased in the tower, liquid flowing across a plate suffers increasing energy losses due to flow friction, resulting in increased hydraulic gradient. Particularly in columns of large diameter, a liquid flow rate is finally reached where the gradient is large enough to prevent the flow of vapor through the perforations at the upstream end of the plate. On further increasing liquid flow rate, the liquid at the upstream end of the plate may actually "dump" through the perforations so that the plate is by-passed by a portion of the liquid stream.

Bubble-cap plates also experience the phenomena of "dumping" and "priming." The caps are constructed, however, so that they will function properly over a wider range of vapor and liquid rates than the perforated plates.

At the present time there is little information available in the literature which is of value in predicting either pressure drop or hydraulic gradient for a perforated plate. It is hoped that this thesis will be a substantial contribution for making such predictions.

B. Limitations of the Investigation

All data in this investigation were taken for an air-water system. In general, maximum superficial air velocity was 7 ft. per sec., while the maximum water flow rate was 24 gpm per ft. of plate width. Data for higher water rates could not be taken since the plate operation became unstable at higher rates with the air velocities attainable. While these rates are not the maximum rates used commercially, it is believed that the rates do cover the ranges ordinarily encountered. The minimum superficial air velocity included in this investigation was 5.7 ft. per sec., since at lower air velocities the plate became unstable. The minimum water flow rate was zero.

The maximum exit weir height for standard operation was 1 inch. With higher weirs, it was found impossible to operate the plate stably at the air velocities attainable with the apparatus.

The limiting factor for maximum weir heights and liquid rates was found to be the capacity of the air blower. By covering one-half to three-quarters of the perforated area, the maximum superficial air velocity was increased to about 25 ft. per sec., while the maximum water rate was increased to about 90 gpm per ft. of plate width. With three-quarters of the perforated plate covered, the plate operation was observed to be promising at a superficial air velocity of about 20 ft. per sec. with a seal of about 5 inches of clear water.

With one-half of the plate covered, some quantitative data were taken using a 1 1/2" exit weir. The superficial air velocity in this case was about 12 ft. per sec., while the water rate was varied from no flow to about 50 gpm/ft. Some qualitative observations were made at this air velocity using a 1" exit weir. Starting with a low water rate, the operation was stable. Increasing the water rate, a point was reached where the plate was unstable (approximately 40 gpm/ft.). In this region of operation, masses of foam moved back and forth diagonally across the plate giving a "washing machine action." This action "dumped" large quantities of water through the plate. As the water rate was increased, the above action gradually disappeared until the plate was operating with fair stability at a water rate of about 65 gpm/ft. The high velocity of the water across the plate evidently allowed no chance for these oscillations to take place. With further increase in water rate, the stability continued to improve until the operation of the plate, at a water rate of about 90 gpm/ft., appeared to be as good as, if not superior to, the operation at any other range of water rate.

In conclusion, the ranges of water and air rates used are considered to be representative of those which might be encountered in industry.

C. Terminology

Dry Plate - A perforated plate with no liquid on it, i.e., completely dry.

Dumping - The action of a plate when liquid flows down through the perforations so that the plate is by-passed by a portion of the liquid.

Hydraulic Gradient (Δh) - The difference in head between any two points on a plate. Unless otherwise stated, the difference in head between the inlet calming section and the outlet calming section.

Hydrostatic Head - (h) - The pressure exerted at any point in the liquid by the liquid above. Unless otherwise stated, the pressure exerted on the plate at any point along its length by the liquid above.

Instability - A plate is considered unstable when the quantity of water passing down through the perforations becomes greater than 0.2 gpm/ft.^{2} of perforated area.

Priming - If the level of the liquid at the upstream side of the plate plus the height of the liquid column within the downspout, equivalent to the pressure drop between plates, exceeds the height of the downspout, liquid will back up the downspout to the plate above. This action is referred to as priming.

Seal - The height of clear liquid present on the plate. Unless otherwise stated, the hydrostatic head at the downstream calming section expressed in inches of clear liquid.

Superficial Air Velocity - The air velocity based on the area of the bubbling section expressed in ft. per sec. Since data of this investigation were limited to regions of stable operation, the area of the bubbling section was 4.17 square feet.

Total Plate Pressure Drop (h_{π}) - The difference in pressure between the vapor in the space below the plate and the vapor above the liquid on the plate.

Wet Plate - A perforated plate with liquid, either standing on it or flowing across it.

D. Previous Work

Previous investigations of hydraulic gradient have been confined largely to bubble-cap plates. The most recent work was carried out by Klein (6) using an air-water system. He was able to correlate successfully the hydraulic gradient on a bubble-cap plate with operational variables by the use of a Fanning-type friction expression. His conclusion was that the hydraulic gradient on a plate is a result of the frictional losses suffered by the liquid in flowing across the plate. It has been found that frictional drag is much higher for aerated than for non-aerated flow. The energy lost as a result of friction is compensated by a loss of hydrostatic head which produces the hydraulic gradient. Klein found that the hydraulic gradient increases with increased liquid rate, increases slightly with increased air rate up to the point of complete aeration, and decreases with increased skirt clearance, seal, and weir height. Based on the gradient correlation, a relatively simple design procedure for the prediction of hydraulic gradient was developed depending only upon the exit weir height and the liquid rate.

The operation of perforated plate columns has been investigated by Kirschbaum (5). He found that perforated plate efficiency, general conditions being equal, is superior to that of a cap-type plate. With decreasing vapor velocity, efficiency drops off rapidly because of liquid dripping through the plate ("dumping"). In columns with plate spacing great enough to prevent entrainment from becoming an important factor, enrichment increases as vapor velocity increases until the optimum load is exceeded. It then decreases evenly because of decreased vapor-liquid contact time. At excessive vapor velocity, the perforated plate pressure drop is so excessive as to cause "priming." Kirschbaum mentions also that the capacity of perforated plates to carry low vapor loads diminishes as plate diameter increases, while the upper load limit, imposed by "priming," stays almost constant. Plates of larger diameters also exhibit better efficiencies in their operating range.

Kirschbaum attributes the pressure drop of the vapor between plates to two types of losses; a static loss due to the head of liquid on the plate, and a streaming loss which is analogous to fluid flow through an orifice and is a function of the square of the superficial vapor velocity. The pressure drops encountered by Kirschbaum may have been excessive because he employed plates with small perforations on relatively large centers. A representative plate used by him had 2.5 mm. holes on 9 mm. equilateral triangular centers.

Kirschbaum also investigated increasing efficiency by employing atomizing effects on perforated plates using no exit weir. He found that the atomizing effect was not sufficiently perfect to obtain rectification comparable to that which can be realized with the foam layer using a weir. He also tested a corrugated plate with holes in the sides of the corrugations. With this plate and no weir, he obtained a cross-current, atomizing effect between liquid and vapor. The results proved no better.

Kirschbaum's work is valuable from a qualitative point of view because he tested various modifications of the perforated plate. By varying perforation diameter and pitch, he obtained varying amounts of vapor passage area. Increasing the area of vapor passage decreased the plate pressure drop but did not remove the dependence of the pressure drop on the square of the vapor velocity. He found that too small a ratio of pitch to diameter for the perforations led to merging of vapor streams above the holes and, therefore, loss in efficiency of vapor-liquid contact. However, Kirschbaum attempted no quantitative correlation of hydraulic gradient and pressure drop with vapor and liquid loading.

The perforations on a perforated plate function as submerged orifices. McGoldrick (7) attempted a correlation of the pressure drop through a single submerged orifice with vapor velocity and liquid head above the orifice. Using various liquids and air as a vapor, he found that the pressure drop through an 1/8 in. orifice and liquid above was affected by the liquid height, air rate, liquid surface tension, and liquid density. He proposed the following correlation for an air-water system:

$$P_w = 0.0032\,(Q)^2 + H_h + X$$

Where P_w = total pressure drop in inches of water.

Q = volumetric rate of air flow in cubic feet per hour through the 1/8 in. orifice.

H_h = Hydrostatic head in inches of water.

X = Correction factor due to surface tension.

This correlation indicates that the pressure drop corrected for hydrostatic head is essentially that of air through a dry orifice. McGoldrick found the surface tension corrections to be small in comparison to the other factors and essentially constant. However, at high vapor rates, the air funnels through the liquid and the surface tension factor becomes negligible. The dry orifice loss is similar to that predicted by Kirschbaum (5).

McGoldrick fails to present a general correlation for the pressure drop through a submerged orifice, since his equation involved the experimental factor X. Robinson and Gilliland (8), however, suggest the following equation for the pressure drop through the perforations:

$$h_{\pi} = 0.04\frac{\gamma}{d\rho_L} + \frac{\rho_V}{\rho_L}V_{\pi}^2$$

Where h_{π} = pressure drop through perforations, inches of liquid.

γ = surface tension, dynes per cm.

ρ_V = vapor density, lb. per cu. ft.

ρ_L = liquid density, lb. per cu. ft.

V_{π} = velocity based on total perforation area, ft. per sec.

d = diameter of perforation, in.

Kirschbaum and Andrews (4) have found that incorrect leveling produces uneven liquid distribution to a greater degree with perforated plates than with bubble-cap plates. With low vapor velocities, it was impossible to arrange conditions so that equal distribution of vapor flow was maintained over the whole surface of the plate, although the plate could be precisely leveled with adjusting screws.

Gunness and Baker (2) made extensive tests on a 5 1/2 ft. diameter beer still being used to separate alcohol from a beer mash. Perforated plates with 1/2 in. holes on 1 1/8 in. equilateral triangular centers were employed at 18 in. spacings in the column. Each plate had 2,500 perforations. Rates of flow and pressure drops over each plate were measured. The column operated at a feed rate of 720 lb./min. and a steam rate of 162 lb./min. Pressure drops per plate averaged between 2 and 3 in. H_2O with a vapor velocity of 17 ft./sec. through the perforations. The results indicated that the perforated plates gave efficiencies lower than those attainable with bubble-cap plates. The nature of the mash made use of perforated plates desirable because of the difficulty involved in cleaning clogged cap plates. The investigators made runs just after the plate had been cleaned and also several weeks after the column had been in operation. The fact that perforated plates can efficiently handle contaminating liquids is borne out by the results.

The most recent quantitative investigation concerning hydraulic gradient on perforated plates was carried out by Hutchinson, Buren and Miller (3). The objective of their investigation was to obtain data which would indicate the type of liquid depth to be used for hydraulic gradient correlations. They developed a theoretical analysis of aerated flow which indicated that the proper depth factor for correlation was an effective aerated seal (that is, the hydrostatic head of the foam measured in terms of clear liquid flowing). They correlated their data on this basis.

The investigation was carried out on a stainless steel plate having 1/8 in. perforations on 3/16 in. equilateral triangular centers with the long dimension parallel to liquid flow. The perforated area was 23 in. wide and 47 in. long, the upstream calming section varied from 16 in. to 30 in., and the downstream calming section was 20 in. long. The length of the aerated section was varied from 47 in. to 30 in. by blanking off the upstream holes, and the width was reduced by half for high liquid rates (over 2,000 gph/ft.). Three sets of runs were made with a 1% forward tilt of the plate. Superficial air velocities up to 9 ft./sec. and liquid rates up to 4,000 gph/ft. were used.

Hutchinson, Buren and Miller found it necessary to consider the effects of aeration in interpreting fluid flow data on the perforated plate. These effects were included in the correlation by the following factors:

$$\text{Aeration factor } \beta = \frac{\Delta P_a - \Delta P_b}{\rho_W (S_a - S_b)}$$

$$\text{Density factor } \Phi = \frac{\text{aerated density}}{\text{clear density}}$$

where the subscripts "a" and "b" refer to two liquid depths at the same point on the plate under different flow conditions.

$\Delta P =$ pressure drop through the plate.

$S =$ clear liquid head on the plate.

$\rho_W =$ clear liquid density.

They also found that:

1. Hydraulic gradient increased with increased liquid rate.
2. The gradient decreased with increased seal.
3. For a sloped plate, the absolute gradient increased compared to a flat plate under the same conditions, but the gradient relative to the sloped plate decreased.
4. There was a logarithmic variation of gradient with average seal.
5. The gradient decreased with decreased length of the aerated section.

The previous literature appears to lack suitable correlations of both hydraulic gradient and pressure drop with the variables; liquid rate, vapor rate, and weir height. The object of this thesis is to make these correlations.

III PROCEDURE

A. Experimental Program

To develop a correlation for the pressure drop on a perforated plate, it was felt necessary to first investigate the pressure drop with no liquid on the plate. These data led to the conclusion that the pressure drop was similar to an orifice-type loss and could be calculated with the standard orifice equation.

The next step was to see if the pressure drop through the perforations was similar when liquid was held on the plate. For this investigation, data were taken using various weir heights with a negligible liquid flow rate to offset leakage at the downstream weir and through the perforations. The hydrostatic head readings in the bubbling section were averaged and, together with a calculated pressure loss due to surface tension, subtracted from the total plate pressure drop. The remaining loss was that due to passage of the air through the perforations and proved greater than that for a dry plate. During the investigation, it was noticed that although the plate was operating in a stable range, regions of perforations were inactive when the plate was viewed from the underside by means of plastic windows in the air chamber. It was reasoned that this phenomenon was responsible for the excessive pressure drop on the wet plate. The quantity of liquid leaking through the plate was measured and proved to be slight.

Previous work with bubble-cap plates (6) has shown that a Fanning friction factor type expression can be used to correlate hydraulic gradient data. To test its applicability to a perforated plate, runs were made varying liquid and air flow rate and also weir height. The gradient was measured by subtracting the downstream clear liquid level from that upstream. Because of the horizontal direction in which air was led to the air chamber below the plate, the air leaving the perforations had a velocity vector in the downstream direction. This tended to raise the level in the downstream calming section above that in the upstream calming section, giving a reverse hydraulic gradient effect when no liquid was flowing. Several runs were made to measure this effect at various air rates and liquid seals with no liquid flow and a plot of correction values was developed. These corrections were applied to the hydraulic gradients measured during liquid flow runs to make them equivalent to gradients measured on a plate with vertical air flow to the perforations.

Applying the Fanning-type friction factor expression to the hydraulic gradient data as a method of correlation yielded results that were quite satisfactory.

To investigate plate operation at high air velocities, it was necessary to blank off the upstream half of the perforated area. Because the air vector effect mentioned above was more pronounced and errors involved in measuring hydraulic gradient doubled, the data taken at high air velocity and high liquid seal proved unsatisfactory. However, the runs served in obtaining qualitative information regarding plate operation.

B. Description of Apparatus

The apparatus used in this thesis was adapted from that constructed by Ghormley (1) and Seuren (9) and more recently used by Klein (6). The apparatus was originally constructed and used for the investigation of the operating characteristics of bubble-cap plates.

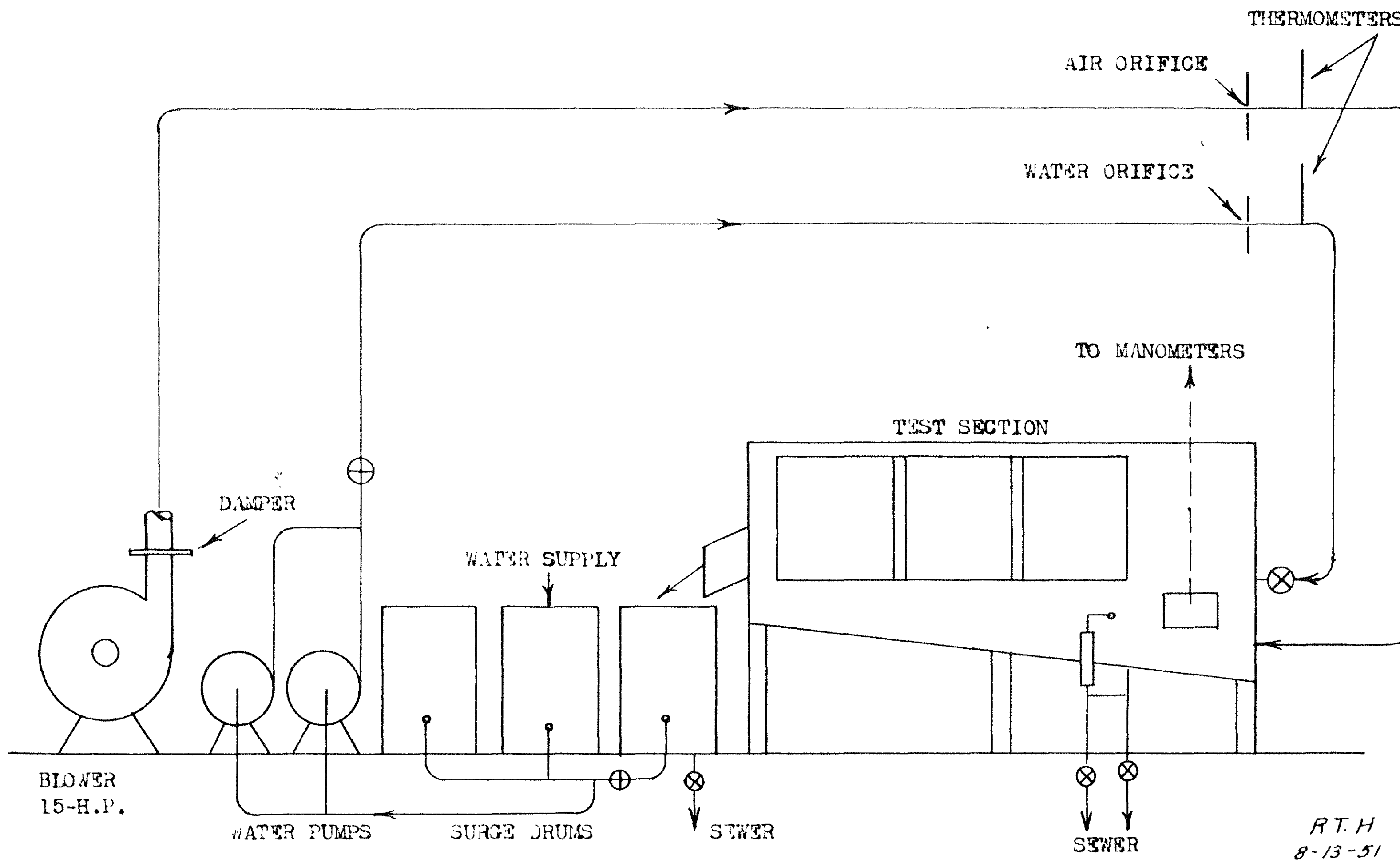
The apparatus consisted of an air-tight chamber which was covered by the perforated plate; a 15-H.P. Sturtevant blower; two 2-H.P. Gould centrifugal pumps; three 55-gallon drums; and various measuring devices, such as manometers and orifices. The region above the plate was enclosed so as to allow for liquid flow. The forward side was constructed of three panes of glass to allow observation of action on the plate. Two plastic windows were located in the air chamber enabling observation of the underside of the plate during operation.

Figure 1 is a schematic representation of the apparatus. The blower was joined to the air-tight chamber by means of an 8-inch duct, making it possible to force air through the perforated plate. The maximum air capacity was 2,000 cfm against atmospheric pressure. The air rate was regulated by means of a slide damper in the blower discharge line and was measured by means of an orifice.

Water was pumped over the perforated plate from the three drums, which were joined in parallel, by the two centrifugal pumps connected in parallel having a maximum capacity of 140 gpm. The water rate was controlled by a globe valve in the 2-inch water line leading from the pumps to the upstream end of the perforated plate and was measured by an orifice. An inlet weir was used to insure even distribution of the water flow across the plate section. In succession, the water flowed through an inlet calming section, over the perforated section of the plate, through an outlet calming section, and over an adjustable

FIGURE 1

FLOW DIAGRAM OF APPARATUS



outlet weir to the surge drums completing the cycle.

The perforated plate was constructed from 14 gauge steel sheet by Wickwire Spencer, Inc., to the following approximate dimensions:

Over-all dimensions	120" x 13 1/2"
Upstream edge to inlet weir	12"
Length of inlet calming section	24"
Length of perforated section	60"
Width of perforated section	10"
Length of outlet calming section	24"

The perforations were 1/8" diameter on 1/4" equilateral triangular centers, the long dimension parallel to liquid flow. Figure 2 indicates the location of taps in the plate which allowed measurement of the hydrostatic head at various points along the length of the plate. These taps were connected to open-end manometers. Also indicated in Figure 2 are the three taps located in the air chamber for measuring the total plate pressure drop. These taps were connected to open-end water manometers.

For the runs in which no liquid was used on the plate, straightening vanes were inserted beneath the plate and perpendicular to the air flow for better air distribution and to produce a more vertical air flow through the perforations. These vanes were removed during runs with liquid on the plate because they reduced air flow through the perforations directly above them.

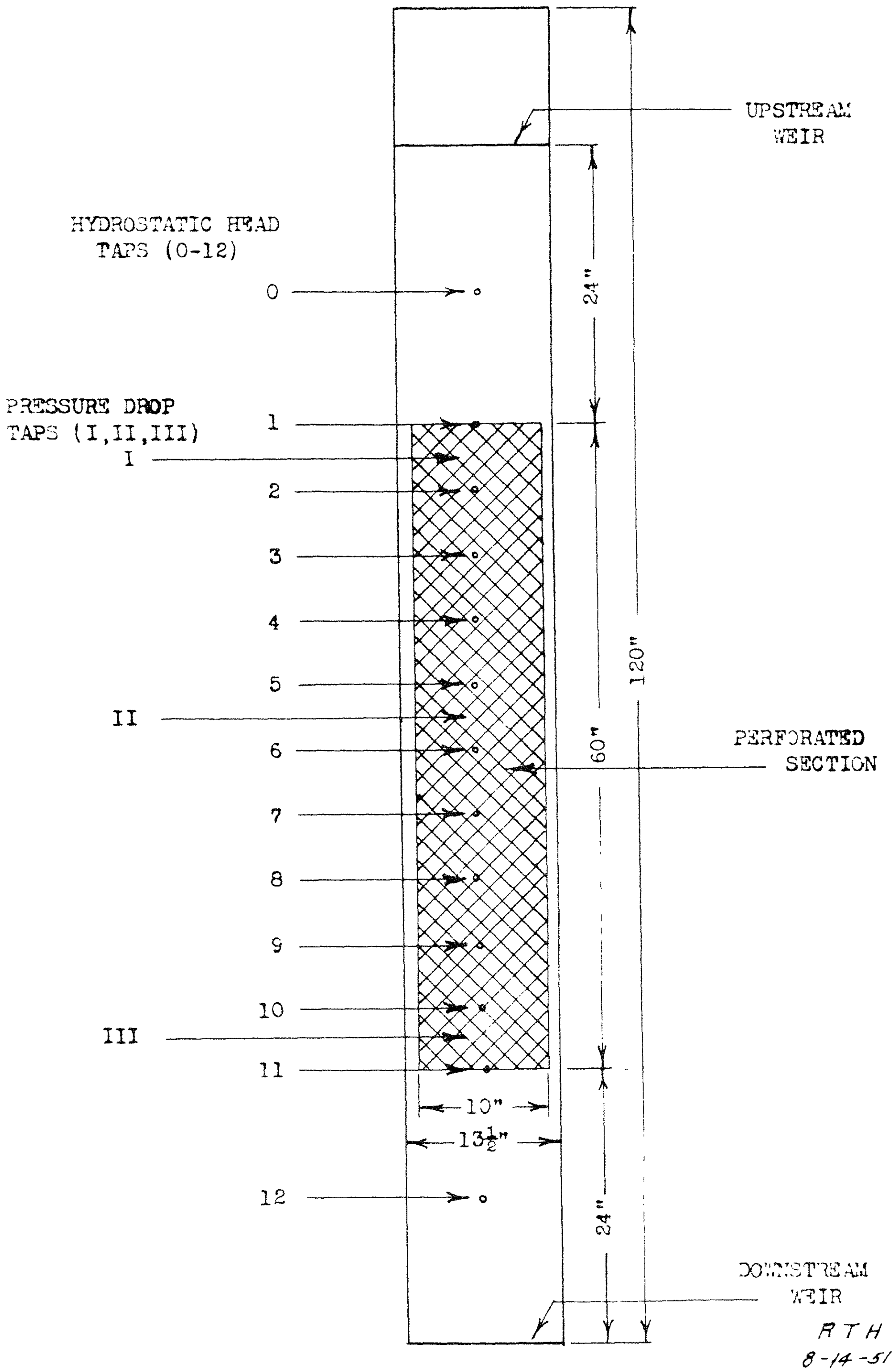
C. Experimental Procedure

The operation of the apparatus was essentially the same for all runs in which liquid was used. A typical run is outlined below:

1. The hydrostatic head manometer lines were purged of air by forcing water through them from the plate taps. After this

FIGURE 2

PERFORATED PLATE LAYOUT



procedure, the water levels in the manometers should be the same and should lie on a horizontal line. If they did not, adjustments were made to level the plate by means of leveling bolts on the legs of the apparatus. (See Appendix for details of plate leveling.)

2. The desired exit weir was installed.
3. The air blower was started with the damper fully opened.
4. The pump (or pumps) was started and the globe valve in the water line adjusted for proper flow rate.
5. With the plate covered with water and liquid flowing over the exit weir, the air damper was adjusted to give the desired flow rate.
6. The lines leading to the pressure drop taps were drained of any water that had collected in them. The taps themselves were shielded against water droplets from the plate, and the draining procedure was necessary only during very unstable plate operation.
7. After about three minutes were allowed to reach steady state, readings were taken of the hydrostatic head manometers, the plate pressure drop manometers, the water and air orifice manometers, the air temperature, the air pressure upstream of the air orifice, and the weir height.

D. Method of Correlation

1. Hydraulic Gradient

The hydraulic gradient data were correlated by a Fanning friction factor type expression by plotting a modified friction factor as a function of the Reynolds number.

2. Pressure Drop

The pressure drop data were correlated by plotting the air velocity through the perforations against the pressure drop of the air passing through the perforations. With both the dry and the wet plate, curves were obtained which indicated the dependence of the pressure drop through the perforations on the square of the air velocity.

A complete description of the above correlations is given in the section titled DISCUSSION OF RESULTS.

IV RESULTS

The hydraulic gradients measured on the plate and corrected for the air velocity vector (see Section III) are shown in Figures 3 and 4 plotted against the operational variables. In Figure 3 the hydraulic gradient is plotted against the water rate at various weir heights. Figure 4 shows the effect of air rate on the hydraulic gradient at various weir heights. It can be seen that increasing water rate and decreasing weir height both tend to increase the hydraulic gradient, whereas varying the air rate has little effect on the gradient. This latter feature indicates that operation was in the range of full aeration and verifies Klein's (6) conclusion that hydraulic gradient is independent of vapor velocity. The trend of the 1-inch weir data in Figure 4 might indicate that aeration was not complete at the low air rates with this liquid level.

The pressure drop on a dry perforated plate is plotted against air rate in Figure 5. The straight line with a slope of two on logarithmic paper indicates the dependence of the pressure drop on the square of the air velocity.

The total plate pressure drops are shown in Figures 6 and 7 plotted against the operational variables. Figure 6 is a plot of the total pressure drop against air rate at various weir heights with negligible water flow. The effect of the water flow rate at various weir heights on the total pressure drop is illustrated in Figure 7. The total plate pressure drop can be seen to increase with increasing air rate, liquid rate, and weir height.

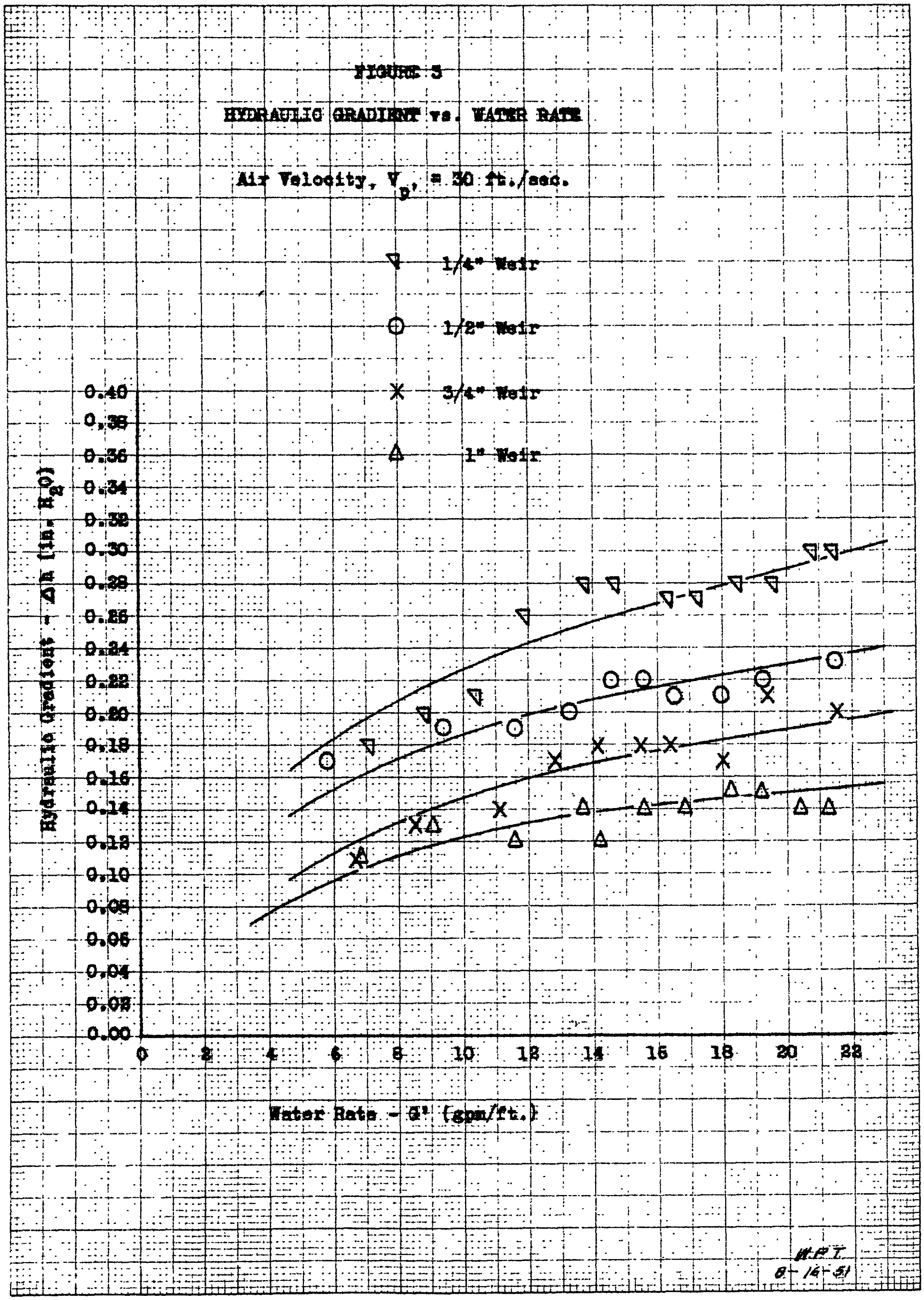


FIGURE 5
HYDRAULIC GRADIENT vs. WATER RATE
Air Velocity, V_p, = 30 ft./sec.
1/4" Weir
1/2" Weir
3/4" Weir
1" Weir
Hydraulic Gradient - Δh (in. H_2O)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.36
0.38
0.40
0
2
4
6
8
10
12
14
16
18
20
22
Water Rate - G' (gpm/ft.)
W.P.T.
8-14-51

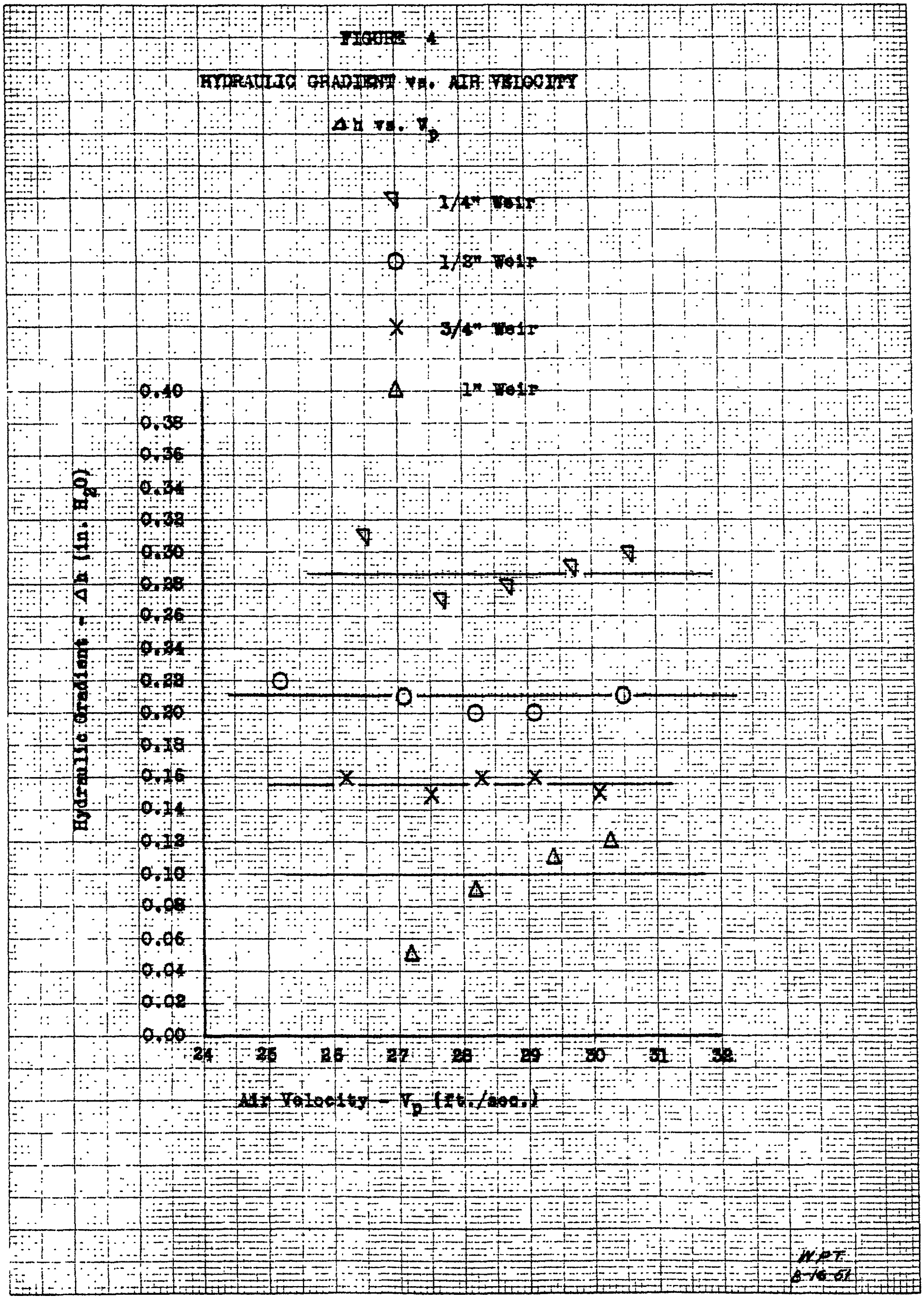


FIGURE 4
HYDRAULIC GRADIENT vs. AIR VELOCITY
Δh vs. V_p
1/4" Weir
1/8" Weir
3/4" Weir
1" Weir
0.40
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
24
25
26
27
28
29
30
31
32
Hydraulic Gradient - Δh (in. H2O)
Air Velocity - V_p (ft./sec.)
WPT
8-16-61

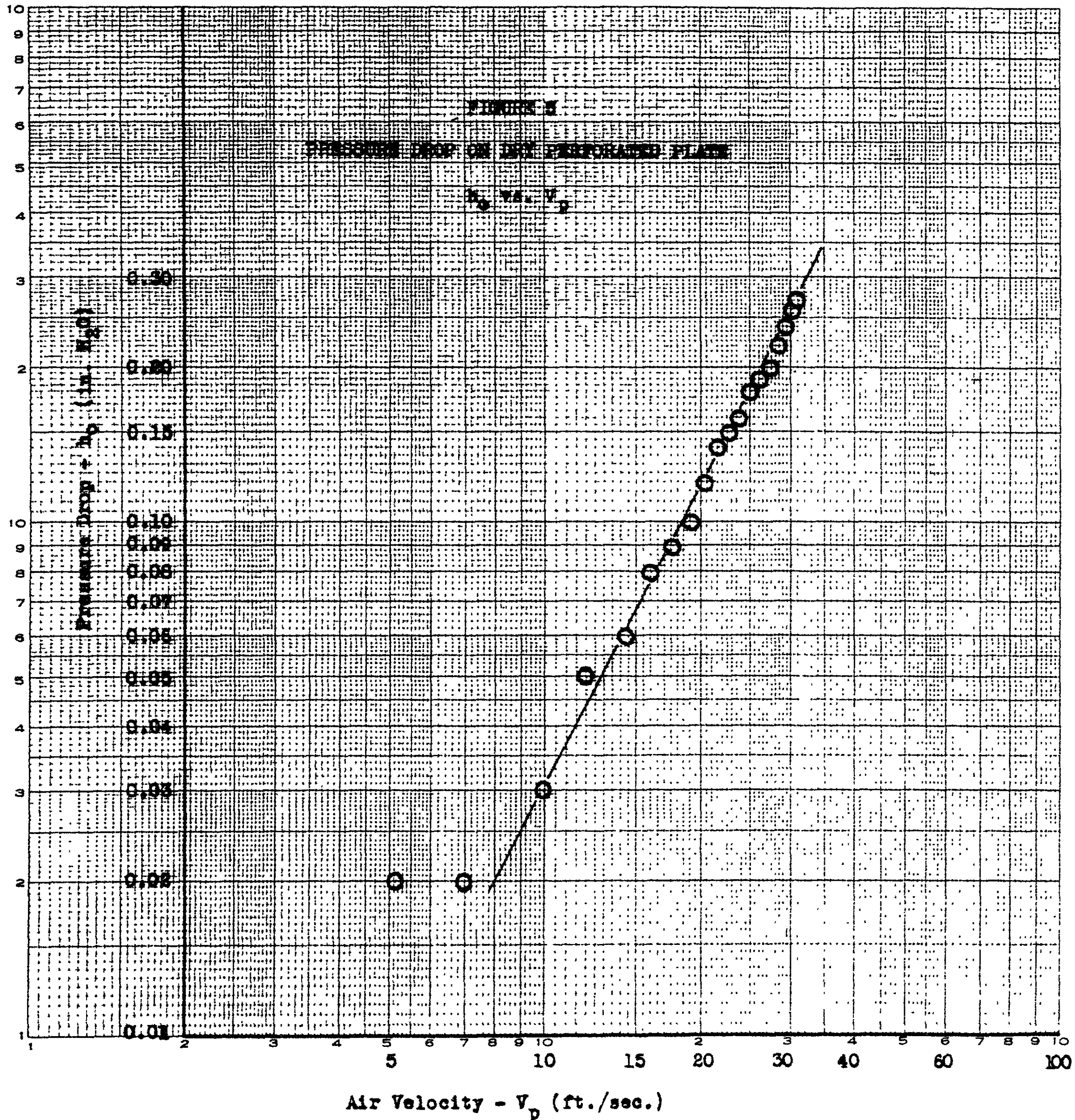


FIGURE 5
PRESSURE DROP ON DRY PERFORATED PLATE
h_o vs. V_p
Pressure Drop - h_o (in. H_2O)
0.30
0.20
0.15
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
5
10
15
20
30
40
60
100
Air Velocity - V_p (ft./sec.)

W.P.T.
8-11-51

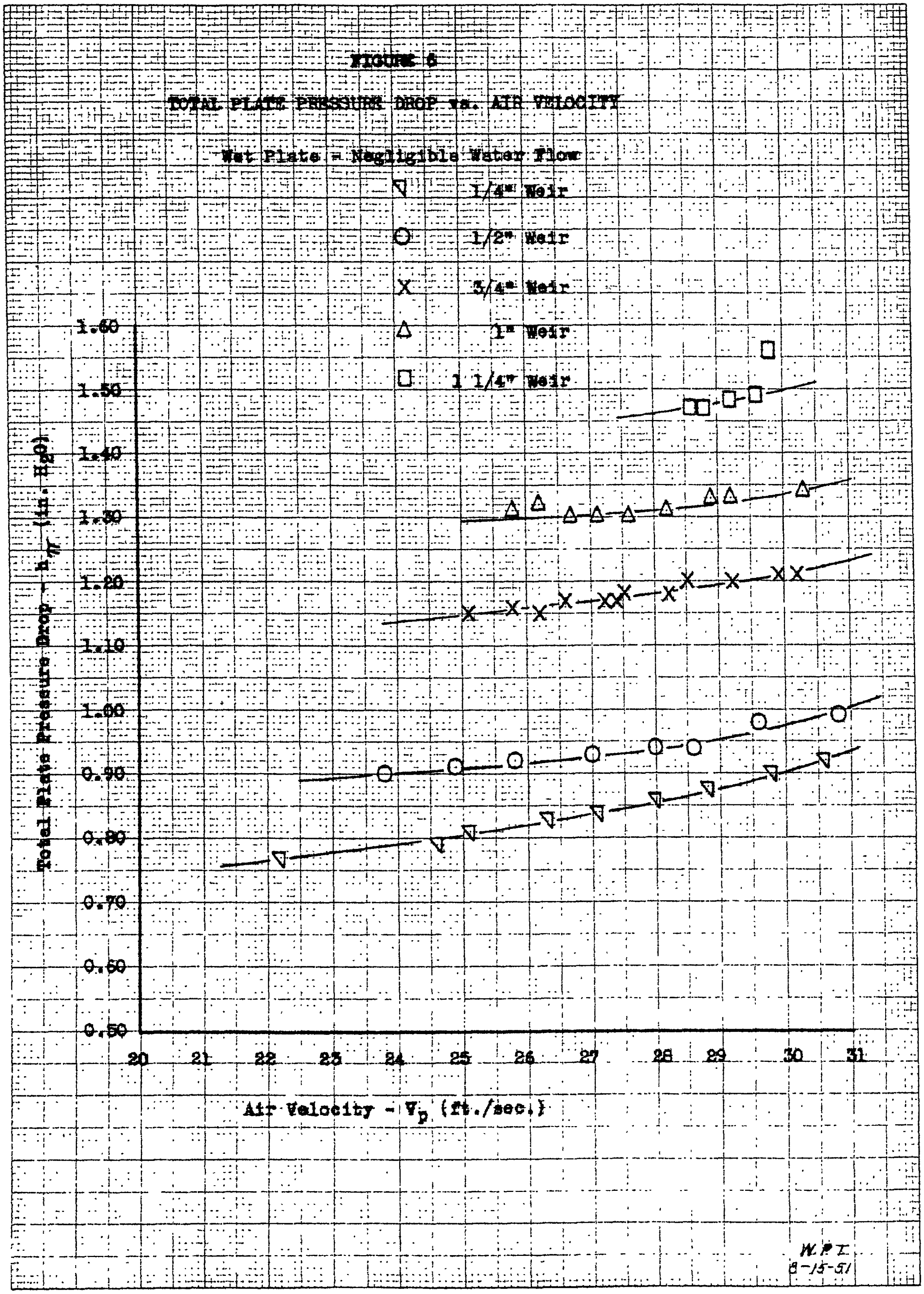


FIGURE 6
TOTAL PLATE PRESSURE DROP vs. AIR VELOCITY
Wet Plate - Negligible Water Flow
1/4" Weir
1/2" Weir
3/4" Weir
1" Weir
1 1/4" Weir
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
Total Plate Pressure Drop - h_T (in. H_2O)
20
21
22
23
24
25
26
27
28
29
30
31
Air Velocity - V_p (ft./sec.)
W.P.T.
8-15-51

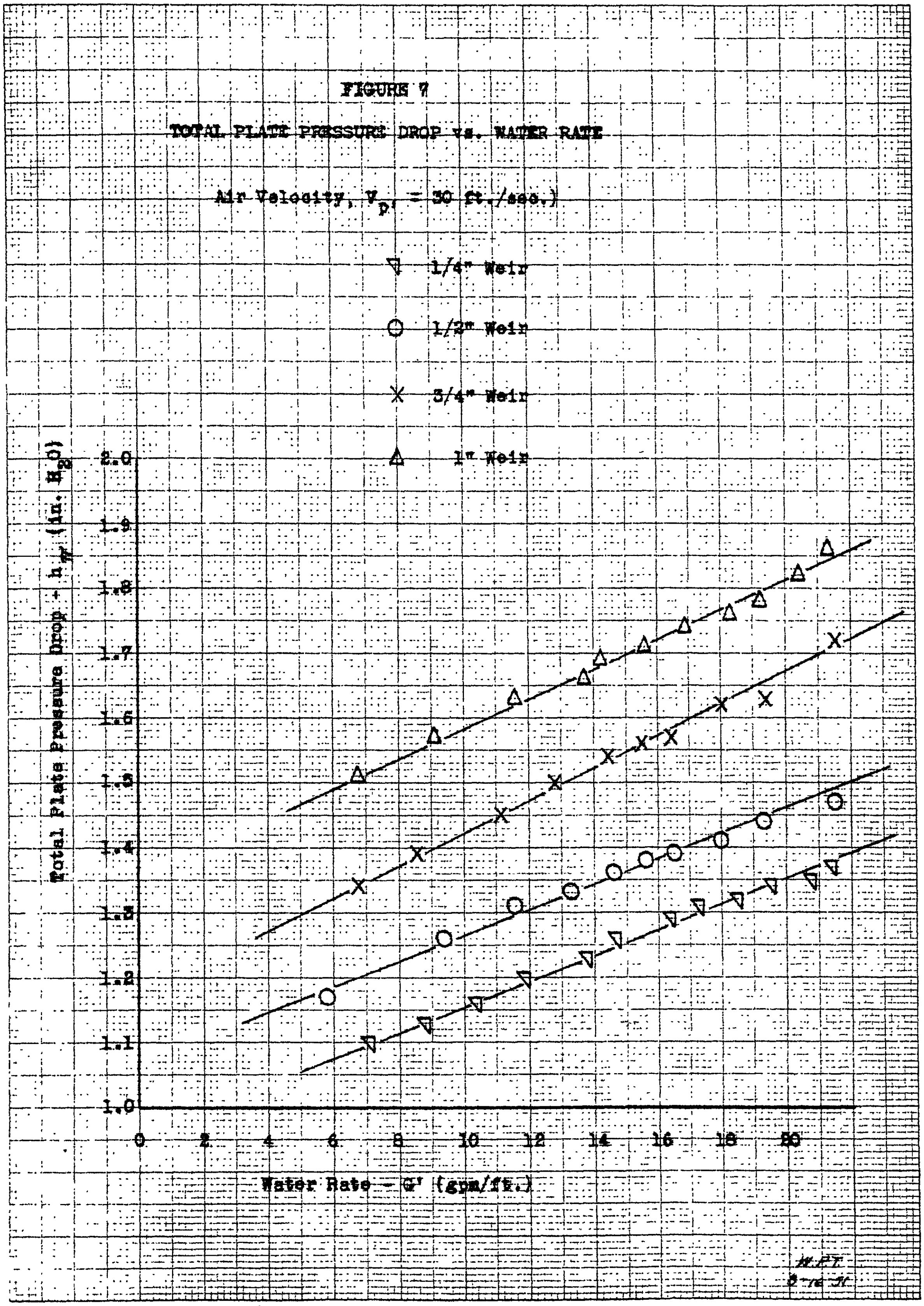


FIGURE 7
TOTAL PLATE PRESSURE DROP vs. WATER RATE
Air Velocity, V_p, = 30 ft./sec.)
1/4" Weir
1/2" Weir
3/4" Weir
1" Weir
Total Plate Pressure Drop - h_T (in. H_2O)
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0
2
4
6
8
10
12
14
16
18
20
Water Rate - G' (gpm/ft.)

The hydraulic gradient and pressure drop data shown in these Figures were used to develop correlations and methods of prediction (see Section V - DISCUSSION OF RESULTS).

The main results of this thesis are:

A. A correlation for the hydraulic gradient data.

B. A calculation procedure for predicting hydraulic gradient.

C. A correlation for the pressure drop data.

D. A calculation procedure for predicting pressure drop.

V DISCUSSION OF RESULTS

A. Hydraulic Gradient Correlation

In his investigation of hydraulic gradient on bubble-cap plates, Klein (6) found the gradient to be independent of vapor velocity after reaching the point of full liquid aeration. He further found that the bulk of the hydraulic gradient occurred in the bubbling section and that the hydraulic gradient data were correlated by means of a Fanning-type friction factor.

A study of the hydraulic gradient data in Figure 4 for the perforated plate both indicates that operation was in the region of full aeration and verifies Klein's conclusion that hydraulic gradient is independent of vapor velocity.

The flow of liquid across a perforated plate is essentially the same as that across a bubble-cap plate. In each case there is a constancy of liquid or foam velocity and area available for flow. It seemed reasonable, therefore, to assume that the bulk of the gradient would occur in the bubbling section of the perforated plate and that the hydraulic gradient data would be correlated by a Fanning-type friction factor.

The hydraulic gradient data were used to calculate a modified friction factor from the expression:

$$F = \frac{f' \, V_f^2 \, N}{2g_c \, r_h} \qquad (1)$$

Where F = energy loss across the bubbling section = $\frac{\Delta h}{24}$ (ft. of H_2O).

Δh = hydraulic gradient (in. of H_2O).

f' = modified friction factor.

V_f = velocity of foam (ft./sec.).

N = length of bubbling section (ft.).

g_c = gravitational constant (ft./sec.^{2}).

r_h = hydraulic radius (ft.).

The hydraulic radius was obtained from the equation:

$$r_h = \frac{bL_c}{b + 2L_c} \qquad (2)$$

Where b = channel width (ft.).

L_c = calculated foam height = twice the downstream hydrostatic head (ft.) (6).

The foam velocity was calculated from the equation:

$$V_f = \frac{G'}{(60)\ 7.46\ L_c \phi} \qquad (3)$$

Where G' = liquid flow rate (gpm/ft. plate width).

ϕ = fractional volume of the foam occupied by the liquid = 1/3 (6).

The modified friction factor was plotted as a function of the Reynolds number of the foam which was obtained from the equation:

$$Re' = \frac{r_h V_f \rho_f}{\mu_f} \qquad (4)$$

Where Re' = Reynolds number of foam.

μ_f = effective foam viscosity (lb./ft.-sec.).

ρ_f = effective foam density (lb./ft.^{3}).

The foam density, ρ_f , is essentially the weight of liquid contained in a unit volume of foam. Since ϕ is defined as the fractional volume of foam occupied by the liquid, it follows that ρ_f may be calculated from the expression:

$$\rho_f = \rho_l \Phi \qquad (5)$$

Where ρ_l = density of the clear liquid (lb./ft.^{3}).

There being no simple, accurate expression for calculating foam viscosity from the relative amounts of air and water in the foam, a similar expression was used for calculating μ_f:

$$\mu_f = \mu_l \Phi \qquad (6)$$

Where μ_l = clear liquid viscosity.

Any error introduced by use of the above equation affects the correlation only by shifting the plot of the friction factor, f', along the Re' axis.

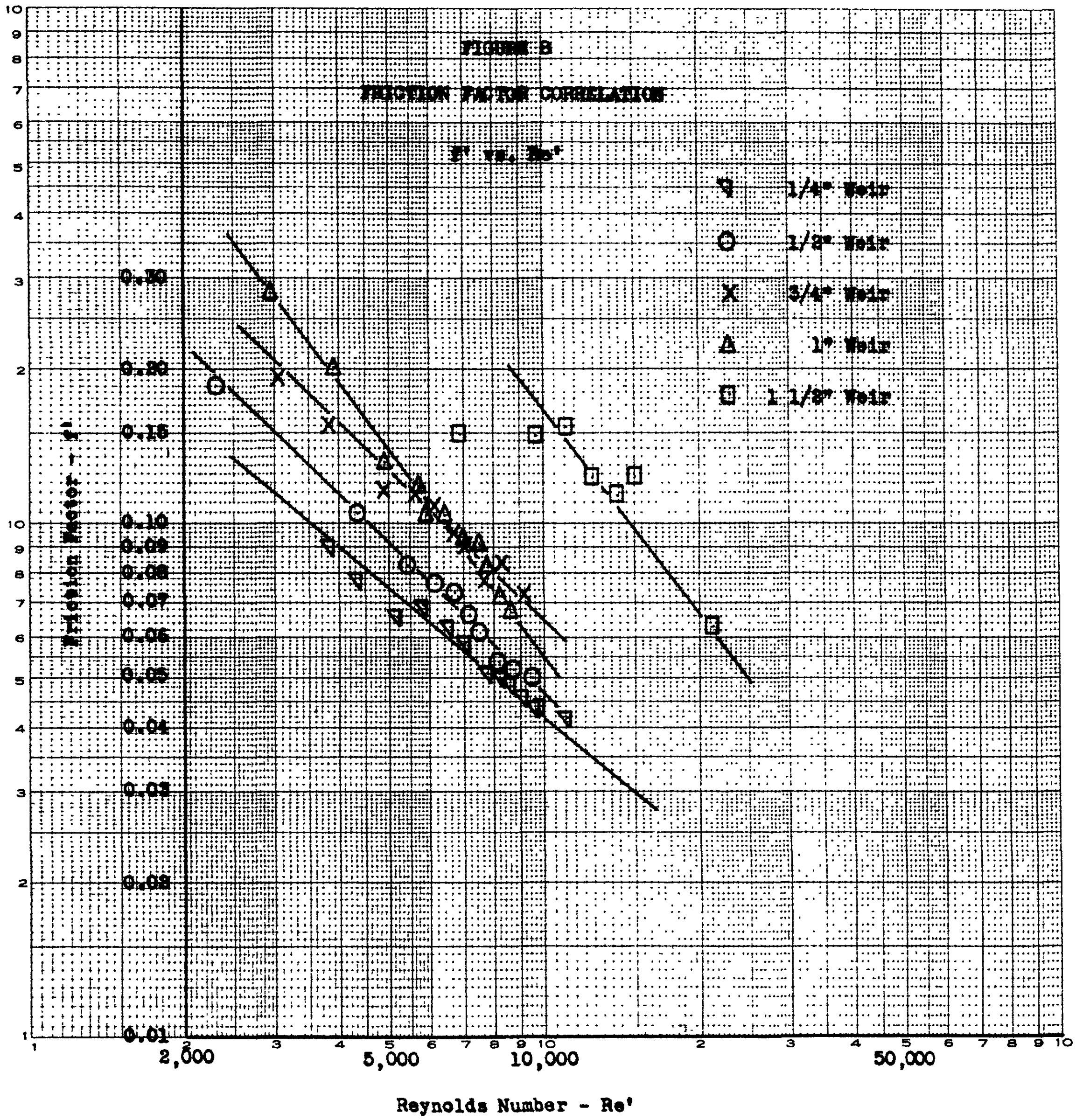
Figure 8 shows the modified friction factor, f', plotted vs. the Reynolds number for various weir heights. The points for each weir height are seen to lie on a straight line. As the weir height and, consequently, the seal increases, the friction factor for a given Reynolds number increases.

It would be convenient to draw the lines for the various weir heights into a single line. Since f' and Re' are dimensionless, the factor used to draw the lines of Figure 8 together should be dimensionless. Several factors were tried, and the factor T was chosen:

$$T = \frac{D_p}{h_c - D_p} \qquad (7)$$

Where D_p = diameter of the perforations (in.).

h_c = downstream hydrostatic head (in. of H_2O).


FRICTION FACTOR CORRELATION
F' vs. Re'
1/4" Weir
1/2" Weir
3/4" Weir
1" Weir
1 1/2" Weir
Friction Factor - f'
0.30
0.20
0.15
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
2,000
5,000
10,000
50,000
Reynolds Number - Re'

W.F.T.
8-13-51

This factor was employed without a theoretical basis and may not apply on a plate with a different perforation diameter or perforation pattern. The plot of f'T vs. Re' is shown in Figure 9. Excluding the data for the 1 1/2" weir, this plot is seen to correlate the data quite well. Since it was found impossible to obtain data for weirs above 1" at the vapor velocities attainable with the apparatus, half of the perforated section was covered in order to obtain the data for the 1 1/2" weir. For all weir heights, it was found necessary to correct the hydraulic gradient data for the velocity vector of the air (see Section III). This correction was made for the 1 1/2" weir data and the gradient then doubled so as to correspond to a five foot bubbling section as in the case of the other weir heights. Therefore, any error in either the data itself or in the correction for the air velocity vector was doubled. Since all points for the 1 1/2" weir data lie on the "high" side of the line, it is felt by the authors that the correction for the air velocity vector was in error. It is interesting to note that all points for the 1 1/2" weir data lie along a line parallel to the original line if one point is excluded.

In summing up the above discussion, it was found that hydraulic gradient for the perforated plate could be predicted by use of a modified Fanning equation. The modified Fanning friction factors for various weir heights were found to be correlated by plotting f' x T vs. Re'. Of noteworthy interest is the fact that the modified Fanning friction factor for the perforated plate is about 17% of the same factor for bubble-cap plates with the same weir height and operating at equal Reynolds numbers (6). A comparison of hydraulic gradient data

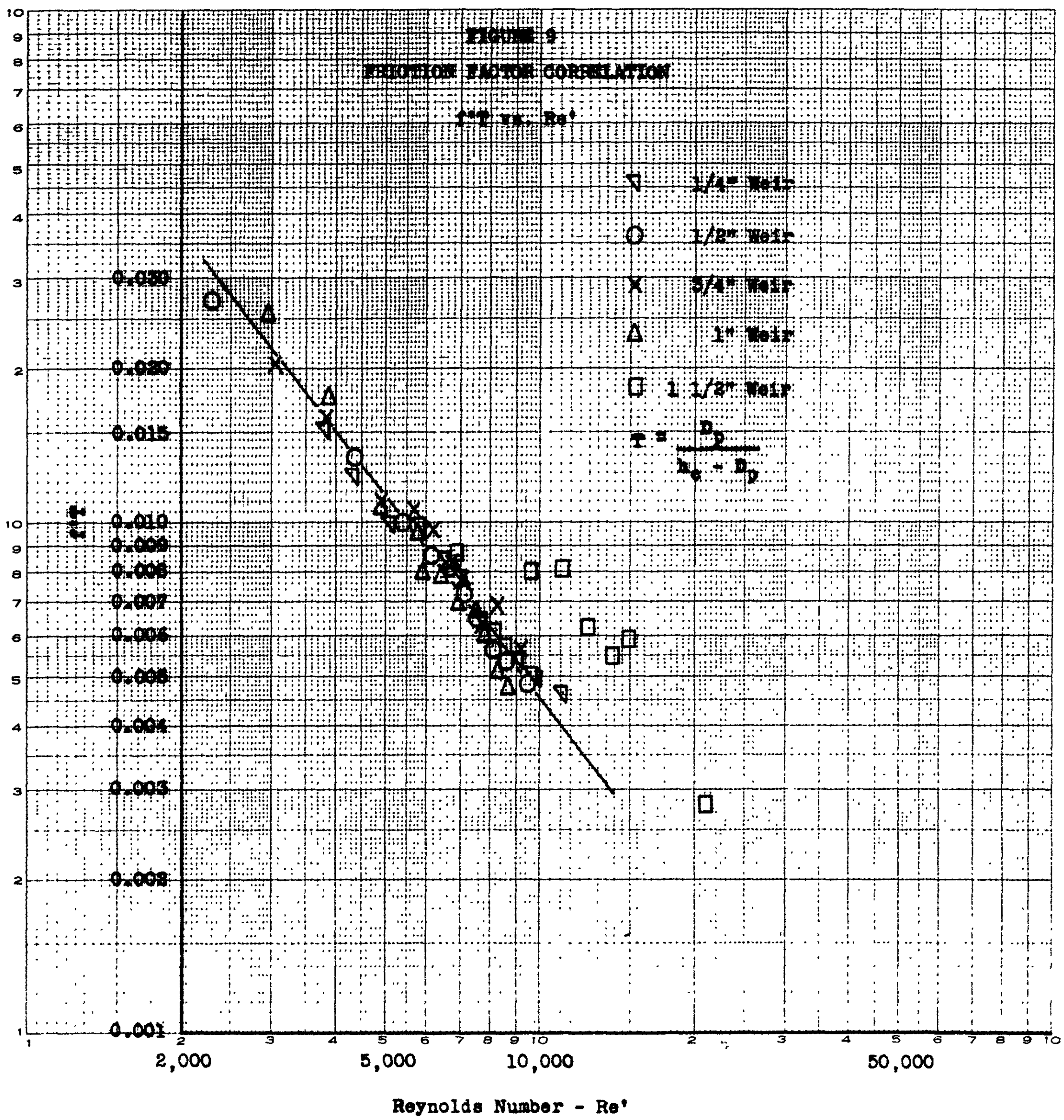


FIGURE 9

FRICTION FACTOR CORRELATION

f"T vs. Re'

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for the two types of plates operating with the same water rate and weir height verifies the fact that hydraulic gradient on the perforated plate is about 17% of that on a bubble-cap plate.

B. Calculation Procedure for Predicting Hydraulic Gradient

On the basis of this investigation, a procedure is offered for calculating hydraulic gradient on a perforated plate operating under stable conditions knowing the liquid flow rate across the plate, the exit weir height, and assuming complete aeration.

1. The downstream clear liquid level, h_c, is determined from the liquid flow rate and the exit weir height by use of the standard weir equation.

2. The foam height, L_c, is twice the downstream hydrostatic head:

$$L_c = \frac{2h_c}{12} \qquad \text{(ft.)}$$

3. The effective foam density, ρ_f, is calculated from the expression:

$$\rho_f = \rho_1 \Phi \qquad \text{(lb./ft.}^3\text{)} \qquad (5)$$

4. The value of L_c is used to determine the hydraulic radius, r_h, and the foam velocity, V_f:

$$r_h = \frac{bL_c}{b + 2L_c} \qquad \text{(ft.)} \qquad (2)$$

$$V_f = \frac{G'}{60 \; \rho_f \, L_c} \qquad \text{(ft./sec.)} \qquad (3)$$

5. The effective foam viscosity, μ_f, is calculated from the expression:

$$\mu_f = \mu_1 \Phi \qquad \text{(lb./ft.-sec.)} \qquad (6)$$

6. The Reynolds number of the foam, Re', is obtained from the equation:

$$Re' = \frac{r_h V_f \rho_f}{\mu_f} \qquad (4)$$

7. Knowing Re', f' is obtained from Figure 8.

8. The hydraulic gradient, Δh, is determined from the modified Fanning equation:

$$F = \frac{f' V_f^2 N}{2 g_c r_h} \qquad (1)$$

Where $\Delta h = 24 F$ (in. of liquid).

C. Pressure Drop Correlation

The drop in pressure of air passing through a perforated plate with no liquid on it was found to be a function of the square of the air velocity and could be represented by the equation:

$$h_o = C V_p^2 \qquad (8)$$

Where h_o = pressure drop through perforations (in. of H_2O).

V_p = air velocity through perforations (ft./sec.).

C = experimental constant = 0.00029.

This is the equation of the straight line in Figure 5, obtained by plotting on logarithmic paper the velocity of air through the perforations vs. the pressure drop across the plate. In order to obtain an equation applicable to vapors other than air, Equation 8 may be converted to the more general standard orifice equation:

$$V_p = C\sqrt{\frac{g_c h_o \rho_l}{6 (1-\beta^4)\rho_v}} \qquad (9)$$

Where V_p = vapor velocity through perforations (ft./sec.).

h_o = pressure drop through perforations (in. of liquid).

ρ_1 = liquid density (lb./ft.^{3}).

ρ_v = vapor density (lb./ft.^{3}).

$\beta^4 = \left[\frac{A_p}{A_s}\right]^2$ Where A_p is the hole area (ft.^{2}) and A_s is the perforated section area (ft.^{2}).

C = experimental constant.

The experimental constant was found to be 0.86. It is believed that this high constant obtained with a dry plate can be accounted for by reasoning that the air streams leaving adjacent perforations interact and flow characteristics result which differ from those peculiar to a single orifice. The tendency is for the pressure drop to be less than for a single orifice at the same air velocity. The constants usually employed with Equation 9 for a single orifice range from 0.60 to 0.80.

The drop in pressure of air passing through a perforated plate with liquid on it was found to consist of the following components:

1. An orifice type loss which could not be calculated using Equation 8.

2. A loss due to surface tension effects.

3. A loss equivalent to the hydrostatic head of the liquid above the perforations.

Orifice type loss. By subtracting the surface tension effect and the hydrostatic head loss from the total plate pressure drop and plotting the remaining plate pressure drop on logarithmic paper against the air velocity, a straight line with a slope of two was obtained. This is illustrated in Figure 10. The equation of this line is:

$$h_o = C\ V_p^{\ 2} \qquad (10)$$

Where h_o = pressure drop through perforations (in. of H_2O).

V_p = air velocity through perforations (ft./sec.).

C = experimental constant = 0.00047.

At equivalent air velocities (based on total area of perforations, A_p), the pressure drop of the air passing through the perforations was found greater for the wet plate than for the dry plate. It is believed that this was caused by partial inactivity of the perforated area which is attributed to the wave motion of the bubbling liquid on the plate. Since the velocities were calculated from the volumetric air rate to the plate and the total hole area, they did not represent the actual velocity in the case of the wet plate with its inactive regions. Assuming that the pressure drop on the wet plate should be the same as that on a dry plate, Equation 8 was used to calculate a velocity from the pressure drop. It was found that about 20% of the perforated area had to be unavailable for air flow during a stable run to cause the higher pressure drop. This agreed with an estimate of 25% inactivity made by viewing the underside of the plate through plastic windows during operation.

Although about 20% of the perforations were estimated to be inactive during a stable run, this portion of the plate was not dumping. Regions of high hydrostatic head seemed to move across the plate in the direction of liquid flow causing the perforations underneath to be inactive. However, the actual leakage caused by this

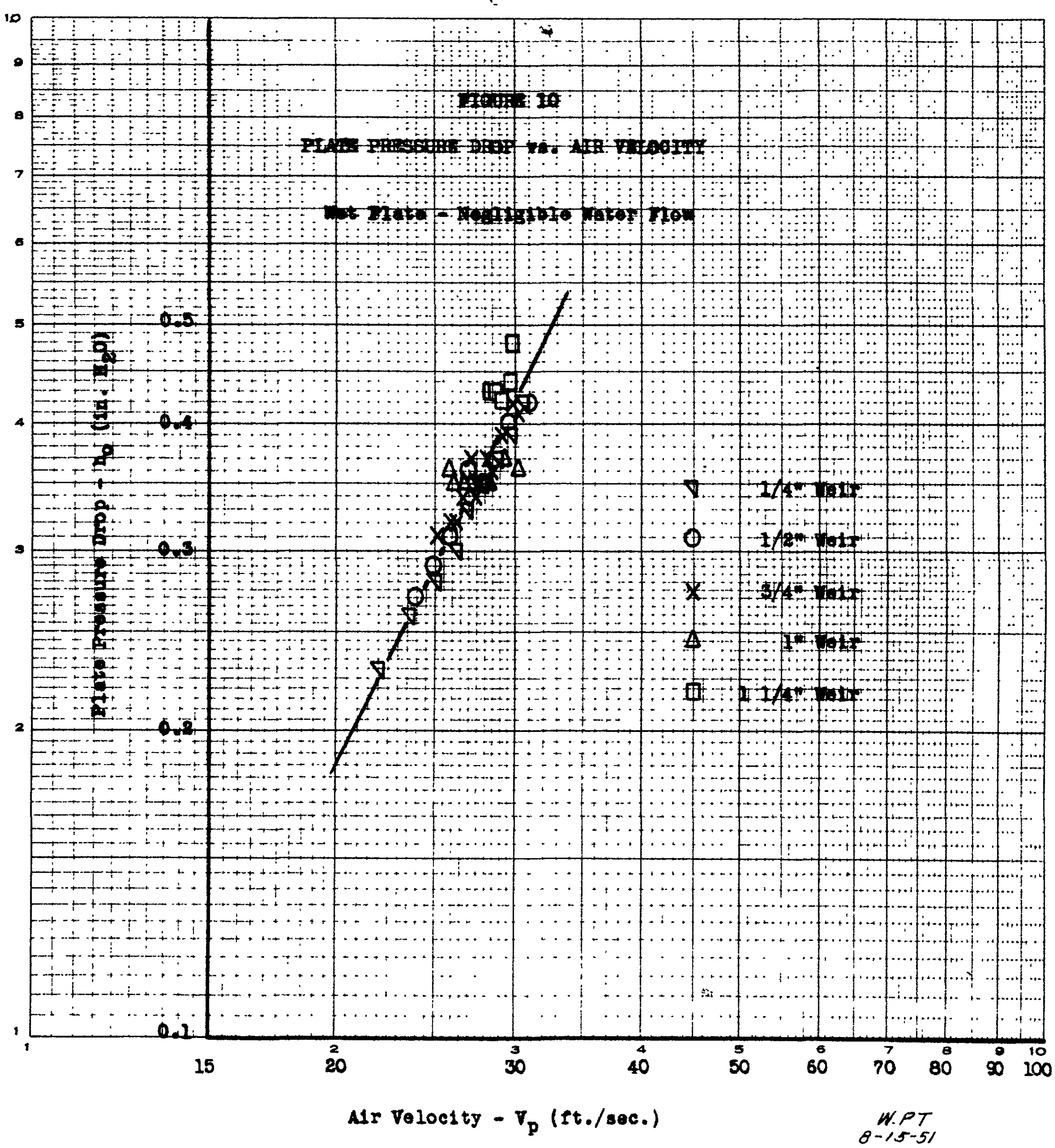
FIGURE 10
PLATE PRESSURE DROP vs. AIR VELOCITY
Wet Plate - Negligible Water Flow
Plate Pressure Drop - h_p (in. H_2O)
0.5
0.4
0.3
0.2
0.1
1/4" Weir
1/2" Weir
3/4" Weir
1" Weir
1 1/4" Weir
15
20
30
40
50
60
70
80
90
100
Air Velocity - V_p (ft./sec.)
W.PT
8-15-51

phenomenon was very slight during stable runs, amounting to approximately 0.015 gpm/ft.^{2} perforated area.

At higher air velocities than could be obtained with the existing apparatus, it is believed that the inactive areas would gradually disappear and the plate pressure drop would then follow Equation 8.

Converting Equation 10 into the more general standard orifice equation, Equation 9, yields an experimental constant of 0.68. This constant obtained with a wet plate is more in line with constants usually encountered for use in Equation 9. However, it is believed that the velocity used to calculate the constant in this equation, V_p, is not the actual velocity on the wet plate as explained above.

An alternative explanation for the constant, 0.68, would be that although regions of inactivity were observed from the underside of the plate, the estimate of 20% inactivity may have been too high and actually most of the area was active. If this were true, the velocity used to calculate the constant would have been correct. It is suggested that the clear liquid layer below the foam and next to the plate greatly reduces the interaction of air streams from adjacent perforations, and flow is more nearly like that through a single orifice. This would explain the fact that the more normal constant of 0.68 applied rather than 0.86 which was found to apply with the dry plate.

<u>Surface tension loss.</u> To account for the loss in pressure due to surface tension effects, the following equation for the formation

of bubble surface was applied:

$$h_t = \frac{0.04\,\gamma}{\rho_1\, D_p} \qquad (11)$$

Where h_t = pressure drop due to surface tension effects (in. of liquid).

γ = liquid surface tension (dynes/cm.).

D_p = perforation diameter (in.).

This loss amounted to 0.37 inches of water for the system studied. McGoldrick (7) found this equation to apply for a single 1/8-inch orifice and for air velocities similar to those encountered in this thesis. The equation was, therefore, employed and proved satisfactory in correlating the pressure drop data.

Hydrostatic head loss. The pressure to be overcome by the air leaving the perforations is equivalent to the hydrostatic head of the liquid above the perforations. The hydrostatic head profile for a perforated plate was found to be similar to that encountered with a bubble-cap plate (6). A region of low hydrostatic head was formed in the bubbling section. It was found that with weirs up to one inch and air velocities (through the perforations) up to 30 feet per second, the average hydrostatic head in the bubbling section was approximately 0.46 times that in the downstream calming section.

Comparing data taken by Seuren (9) of the total pressure drop on a bubble-cap plate with the total pressure drop on a perforated plate operating at the same volumetric air rate and water level on the plate reveals the perforated plate drop to be the lower of the two. Seuren used thirty caps distributed in an area equivalent to the perforated area used in this thesis. At an air rate of 34 cfm/cap and a liquid level of 2.32 in. on the plate with no liquid flow, Seuren measured a total plate pressure drop of 3.10 in. of H_2O. With the same rate of air to the perforated plate, i.e., 1020 cfm, and the same liquid level, a total plate pressure drop of 2.85 in. of H_2O was calculated. This is about 92% of the drop on the bubble-cap plate. The height of liquid above the slots on Seuren's plate was 1.57 in. With this same liquid seal on a perforated plate, the pressure drop would be 2.10 in. of H_2O or 68% of the bubble-cap plate drop.

D. Pressure Drop Calculation Procedure

The vapor velocity through the perforations, the liquid rate and the downstream weir height are sufficient data to predict the total plate pressure drop with the following equation:

$$h_{\pi} = h_o + h_t + 0.46\, h_c \qquad (12)$$

Where h_c = hydrostatic head of the clear liquid in the downstream calming section, calculated with the standard weir formula (in. of liquid).

The value for h_o is calculated from Equation 9 using the constant 0.68. The surface tension effect, h_t, is calculated by using Equation 11.

Although Figure 10 was developed using data for 1/4, 1/2, 3/4, 1, and 1 1/4 inch weirs, with no liquid flow, the validity of extending its use to somewhat higher seals with liquid flow is verified in Table A IV, where calculated and experimental pressure drops are compared. However, it is not recommended that this plot be used for high seals or for liquids with properties differing widely from water.

At higher water rates it is to be noted that the calculated drop becomes increasingly lower than the experimental drop. This is partially explained by the fact that the hydraulic gradient on the plate causes a fringe of the upstream perforations to cease bubbling and in effect reduces the plate hole area. The plot was developed from data with no liquid flow and hence does not include this effect. When the pressure drop is calculated using air velocities corrected for this inactive area, better agreement is obtained between the values of experimental and calculated pressure drop. This is illustrated in Table A IV.

VI CONCLUSIONS

The conclusions to be drawn from this investigation of hydraulic gradient and pressure drop on a perforated plate are as follows:

1. The hydraulic gradient increases with increasing liquid liquid flow rate.

2. The hydraulic gradient increases with decreasing exit weir height.

3. The hydraulic gradient may be predicted by use of the Fanning-type friction expression:

$$F = \frac{\Delta h}{24} = \frac{f' V_f^2 N}{2g_c r_h}$$

Where f' for various weir heights is plotted versus Re':

$$Re' = \frac{r_h V_f \rho_f}{\mu_f}$$

4. The curves of f' vs. Re' for various weir heights may be brought together into a single curve by plotting f'T vs. Re', where:

$$T = \frac{D_p}{h_c - D_p}$$

   This correlation is known to be valid only for the data of this investigation. Further study would be necessary to determine whether or not the correlating factor, T, is applicable to plates of different perforation size or pattern and to systems other than air-water.

5. The hydraulic gradient on a perforated plate is about 17% of that on a bubble-cap plate operating at the same liquid rate per unit of plate width and the same exit weir height.

6. The pressure drop of vapor passing through the perforations of either a wet or dry plate is a function of the square of the vapor velocity.

7. The pressure drop on a dry perforated plate is lower than the pressure drop through the perforations on a wet plate when operating at equal superficial air velocities.

8. The total plate pressure drop increases with increasing vapor velocity.

9. The total plate pressure drop increases with increasing liquid rate and increasing exit weir height.

10. Knowing the vapor velocity through the perforations, exit weir height, and liquid flow rate, the total plate pressure drop may be calculated by use of the equation:

$$h_{\pi} = h_o + h_t + 0.46\, h_c$$

Where h_o may be calculated from the orifice equation:

$$V_p = C\sqrt{\frac{g_c\, h_o\, \rho_l}{6\,(1 - \beta^4)\,\rho_v}}$$

with $C = 0.68$, h_t may be calculated from the equation:

$$h_t = \frac{0.04\,\gamma}{\rho_l\, D_p}$$

11. At the same superficial air velocity, liquid rate per unit of plate width, and liquid depth, the total plate pressure drop through the perforated plate was found to be 92% of that through a bubble-cap plate. Making the same comparison with equal seals (liquid level on perforated plate equal to height of liquid above cap slots on the bubble-cap plate), the total plate pressure drop through the perforated plate was found to be 68% of that through a bubble-cap plate (9).

12. The hydrostatic head profile of a perforated plate in operation is very similar to that of a bubble-cap plate (6).

13. In the range of stable operation, leakage down through the perforations was found negligible.

VII RECOMMENDATIONS

The following recommendations are made for future investigation of hydraulic gradient and pressure drop on perforated plates:

1. Investigate validity of applying the correlations made in this thesis to plates of different perforation patterns and with larger perforations. The factor, T, used in correlating f' vs. Re' for various weir heights would be of particular interest.

2. Investigate validity of applying the correlations made in this thesis to plates operating with higher seals and greater liquid flow rates by adapting the apparatus to deliver greater vapor velocities.

3. Investigate validity of applying the correlations made in this thesis to plates using liquids and vapors with properties different from the air-water system used.

VIII APPENDIX

TABLE A Ia

SUMMARIZED GRADIENT DATA

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Hydrostatic Head (in. H_2O) h_u	h_{av}	h_c	Corrected Hydraulic Gradient Δh (in. H_2O)
E-1	30.9	7.1	0.85	0.31	0.83	0.18
	30.8	8.8	0.92	0.35	0.88	0.20
	30.7	10.4	0.98	0.36	0.92	0.21
	30.7	11.9	1.06	0.41	0.95	0.26
	30.6	13.8	1.13	0.44	1.00	0.28
	30.6	14.7	1.15	0.45	1.02	0.28
1/4" Weir	30.6	16.4	1.20	0.49	1.07	0.27
	30.5	17.3	1.23	0.50	1.10	0.27
	30.5	18.5	1.27	0.51	1.12	0.28
	30.5	19.6	1.30	0.53	1.15	0.28
	30.4	20.8	1.32	0.57	1.15	0.30
	30.4	21.4	1.35	0.57	1.18	0.30
	29.8	24.0	1.43	0.57	1.20	0.34
E-2	30.6	5.8	0.97	0.38	0.95	0.17
	30.6	9.4	1.10	0.47	1.05	0.19
	30.6	11.6	1.18	0.52	1.12	0.19
	30.4	13.3	1.25	0.50	1.18	0.20
	30.4	14.6	1.30	0.54	1.20	0.22
	30.4	15.6	1.32	0.57	1.22	0.22
1/2" Weir	30.4	16.5	1.35	0.57	1.25	0.21
	30.4	18.0	1.37	0.62	1.27	0.21
	30.4	19.3	1.42	0.62	1.30	0.22
	30.2	21.5	1.50	0.65	1.37	0.23

TABLE A Ia (Continued)

SUMMARIZED GRADIENT DATA

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Hydrostatic Head (in. H_2O) h_u	h_{av}	h_c	Corrected Hydraulic Gradient Δh (in. H_2O)
E-3	30.4	6.7	1.25	0.55	1.25	0.11
	30.3	8.5	1.33	0.57	1.30	0.13
	30.2	11.1	1.43	0.62	1.38	0.14
3/4" Weir	30.2	12.8	1.50	0.66	1.42	0.17
	30.2	14.2	1.57	0.68	1.47	0.18
	30.1	15.5	1.60	0.69	1.50	0.18
	30.1	16.4	1.62	0.71	1.52	0.18
	30.0	18.0	1.67	0.73	1.57	0.17
	30.0	19.4	1.72	0.77	1.58	0.21
	29.8	21.5	1.78	0.79	1.65	0.20
E-4	30.0	21.3	1.93	0.86	1.83	0.14
	30.0	20.4	1.92	0.85	1.82	0.14
	30.0	19.2	1.88	0.80	1.78	0.15
	30.0	18.3	1.87	0.80	1.77	0.15
1" Weir	30.2	16.9	1.82	0.78	1.73	0.14
	30.2	15.6	1.78	0.76	1.70	0.14
	30.2	14.2	1.73	0.72	1.67	0.12
	30.4	13.7	1.70	0.73	1.63	0.14
	30.4	11.6	1.63	0.73	1.58	0.12
	30.5	9.1	1.55	0.71	1.50	0.13
	30.5	6.8	1.47	o.65	1.45	0.11

TABLE A Ia (Continued)

SUMMARIZED GRADIENT DATA

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Hydrostatic Head (in. H_2O) h_u	h_{av}	h_c	Corrected Hydraulic Gradient Δh (in. H_2O)
G-1 1-1/2" Weir (Half of Perforated area Covered)	54.4	0.0	1.77	0.22	1.72	0.0
	54.0	18.2	2.37	0.44	2.20	0.14
	53.4	26.2	2.58	0.50	2.35	0.24
	53.0	30.5	2.67	0.56	2.40	0.32
	52.8	34.4	2.75	0.60	2.48	0.30
	52.8	39.1	2.87	0.65	2.58	0.32
	52.6	42.6	2.95	0.70	2.62	0.40
	52.8	53.7	3.15	0.78	2.82	0.36
F-1 1/4" Weir	30.6	15.4	1.20	0.48	1.05	0.30
	29.7	15.3	1.20	0.48	1.05	0.29
	28.7	15.4	1.20	0.50	1.05	0.28
	27.7	15.3	1.20	0.49	1.05	0.27
	26.5	15.2	1.20	0.47	1.02	0.31
F-2 1/2" Weir	30.5	14.4	1.30	0.55	1.20	0.21
	29.1	14.3	1.30	0.56	1.20	0.20
	28.2	14.3	1.30	0.58	1.20	0.20
	27.1	14.2	1.32	0.56	1.20	0.21
	25.2	14.2	1.25	0.54	1.10	0.22
F-3 3/4" Weir	30.1	12.4	1.48	0.64	1.42	0.15
	29.1	12.8	1.50	0.66	1.42	0.16
	28.3	12.6	1.50	0.66	1.42	0.16
	27.5	12.6	1.50	0.64	1.42	0.15
	26.2	12.5	1.40	0.65	1.30	0.16

TABLE A Ia (Continued)

SUMMARIZED GRADIENT DATA

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Hydrostatic Head (in. H_2O) h_u	h_{av}	h_c	Corrected Hydraulic Gradient Δh (in. H_2O)
F-4	30.3	11.5	1.63	0.70	1.58	0.12
	29.4	11.4	1.62	0.72	1.58	0.11
1" Weir	28.2	11.4	1.60	0.76	1.57	0.09
	27.2	11.4	1.50	0.71	1.50	0.05
H-1	57.4	33.1	2.75	0.52	2.50	0.20
	54.8	32.9	2.73	0.57	2.47	0.26
1-1/2" Weir (Half of Perforated area Covered)	53.6	32.9	2.75	0.62	2.50	0.25
	50.2	32.9	2.75	0.67	2.47	0.36
	48.2	32.7	2.75	0.66	2.50	0.40

TABLE A Ib

SUMMARIZED GRADIENT DATA

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Foam Height $L_c = \frac{2h_c}{12}$ (ft.)	Reynolds Number Re' x 10^3	Friction Factor f'	Correlation Factor T	f'T
E-1	30.9	7.1	0.138	3.83	0.0900	0.169	0.0152
1/4" Weir	30.8	8.8	0.147	4.36	0.0785	0.158	0.0124
	30.7	10.4	0.153	5.13	0.0657	0.150	0.0100
	30.7	11.9	0.158	5.83	0.0689	0.145	0.0100
	30.6	13.8	0.167	6.58	0.0627	0.136	0.00854
	30.6	14.7	0.170	7.05	0.0588	0.133	0.00783
	30.6	16.4	0.178	7.77	0.0513	0.126	0.00646
	30.5	17.3	0.183	8.25	0.0502	0.123	0.00617
	30.5	18.5	0.187	8.62	0.0482	0.120	0.00578
	30.5	19.6	0.192	9.10	0.0460	0.117	0.00539
	30.4	20.8	0.192	9.67	0.0435	0.117	0.00510
	30.4	21.4	0.197	9.90	0.0442	0.113	0.00500
	29.8	24.0	0.200	11.10	0.0419	0.111	0.00465
E-2	30.6	5.8	0.158	2.31	0.186	0.145	0.0270
1/2" Weir	30.6	9.4	0.175	4.33	0.104	0.129	0.0134
	30.6	11.6	0.187	5.40	0.0826	0.120	0.0099
	30.4	13.3	0.197	6.15	0.0761	0.113	0.00860
	30.4	14.6	0.200	6.73	0.0731	0.111	0.00812
	30.4	15.6	0.203	7.14	0.0663	0.109	0.00723
	30.4	16.5	0.208	7.52	0.0610	0.106	0.00646
	30.4	18.0	0.212	8.15	0.0535	0.105	0.00562
	30.4	19.3	0.217	8.70	0.0523	0.102	0.00535
	30.2	21.5	0.228	9.53	0.0502	0.096	0.00482

TABLE A Ib (Continued)

SUMMARIZED GRADIENT DATA

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Foam Height $L_c = \frac{2h_c}{12}$ (ft.)	Reynolds Number Re' x 10^3	Friction Factor f'	Correlation Factor T	f'T
E-3	30.4	6.7	0.208	3.05	0.193	0.106	0.0204
	30.3	8.5	0.216	3.82	0.156	0.102	0.0159
	30.2	11.1	0.230	4.90	0.117	0.0952	0.0111
	30.2	12.8	0.236	5.65	0.115	0.0923	0.0106
3/4" Weir	30.2	14.2	0.245	6.18	0.1095	0.0888	0.0097
	30.1	15.5	0.250	6.70	0.0962	0.0870	0.00837
	30.1	16.4	0.254	7.03	0.0905	0.0858	0.00776
	30.0	18.0	0.262	7.65	0.0775	0.0828	0.00642
	30.0	19.4	0.264	8.25	0.0840	0.0822	0.00690
	29.8	21.5	0.275	9.20	0.0730	0.0785	0.00573
E-4	30.0	21.3	0.305	8.63	0.0675	0.0702	0.00474
	30.0	20.4	0.303	8.26	0.0722	0.0706	0.00510
	30.0	19.2	0.296	7.83	0.0834	0.0723	0.00603
	30.0	18.3	0.295	7.48	0.0910	0.0727	0.00661
	30.2	16.9	0.289	6.95	0.0930	0.0745	0.00693
1" Weir	30.2	15.6	0.283	6.45	0.103	0.0760	0.00782
	30.2	14.2	0.279	5.93	0.103	0.0774	0.00798
	30.4	13.7	0.271	5.77	0.119	0.0795	0.00946
	30.4	11.6	0.263	4.92	0.132	0.0822	0.0108
	30.5	9.1	0.250	3.92	0.202	0.0870	0.0176
	30.5	6.8	0.241	2.97	0.280	0.0903	0.0253

TABLE A Ib (Continued)

SUMMARIZED GRADIENT DATA

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Foam Height $L_c = \frac{2h_c}{12}$ (ft.)	Reynolds Number $Re' \times 10^3$	Friction Factor f'	Correlation Factor T	f'T
G-1	54.4	0.0	0.286				
1-1/2" Weir (Half of Perforated area Covered)	54.0	18.2	0.366	6.88	0.149	0.0577	0.0086
	53.4	26.2	0.392	9.65	0.148	0.0538	0.00796
	53.0	30.5	0.400	11.1	0.154	0.0527	0.00811
	52.8	34.4	0.414	12.4	0.123	0.0508	0.00625
	52.8	39.1	0.430	13.8	0.113	0.0488	0.00552
	52.6	42.6	0.436	15.0	0.123	0.0480	0.00590
	52.8	53.7	0.470	21.1	0.063	0.0444	0.00280

TABLE A II

SUMMARIZED PRESSURE DROP DATA

DRY PLATE

Run	Air Rate V_p (ft./sec.)	Average Plate Pressure Drop h_o (in. H_2O)	Calculated Plate Pressure Drop h_o (in. H_2O)
C-3	5.12	0.02	0.008
	6.97	0.02	0.014
	9.99	0.03	0.029
	12.0	0.05	0.042
	14.4	0.06	0.060
	16.0	0.08	0.074
	17.7	0.09	0.092
	19.2	0.10	0.107
	20.4	0.12	0.120
	21.5	0.14	0.134
	22.7	0.15	0.150
	23.7	0.16	0.165
	25.0	0.18	0.185
	26.2	0.19	0.199
	27.5	0.20	0.219
	28.3	0.22	0.231
	29.4	0.24	0.250
	30.1	0.26	0.262
	31.0	0.27	0.279

TABLE A III

SUMMARIZED PRESSURE DROP DATA

LIQUID ON PLATE - NEGLIGIBLE WATER RATE

Run	Air Rate V_p (ft./sec.)	Hydrostatic Head h_{av} (in.H_2O)	Hydrostatic Head 0.46 h_c (in.H_2O)	Experimental Pressure Drop h_π (in.H_2O)	Calculated Pressure Drop* h_π (in.H_2O)	Plate Pressure Drop $h_o = h_\pi - h_t - h_{av}$ (in. H_2O)
D-1	30.6	0.13	0.18	0.92	0.99	0.42
	29.8	0.14	0.18	0.90	0.97	0.39
	28.8	0.14	0.18	0.88	0.94	0.37
	28.0	0.14	0.18	0.86	0.92	0.35
1/4" Weir	27.1	0.14	0.18	0.84	0.90	0.33
	26.3	0.16	0.18	0.83	0.88	0.30
	25.1	0.16	0.18	0.81	0.85	0.28
	23.6	0.16	0.18	0.79	0.81	0.26
	22.2	0.17	0.18	0.77	0.78	0.23
	20.7	0.20	0.18	0.79	Unstable	Unstable
	19.4	0.21	0.18	0.79	Unstable	Unstable
D-2	30.8	0.20	0.28	0.99	1.10	0.42
	29.6	0.19	0.28	0.98	1.06	0.40
	28.6	0.20	0.28	0.94	1.03	0.37
	28.0	0.22	0.28	0.94	1.02	0.35
1/2" Weir	27.0	0.20	0.28	0.93	0.99	0.36
	25.8	0.24	0.28	0.92	0.96	0.31
	24.9	0.25	0.28	0.91	0.94	0.29
	23.8	0.26	0.28	0.90	0.92	0.27
	22.4	0.24	0.28	0.86	Unstable	Unstable
	21.1	0.26	0.28	0.85	Unstable	Unstable

* Calculated using V_p

TABLE A III (Continued)

SUMMARIZED PRESSURE DROP DATA

LIQUID ON PLATE - NEGLIGIBLE WATER RATE

Run	Air Rate V_p (ft./sec.)	Hydrostatic Head h_{av} (in.H_2O)	Hydrostatic Head $0.46\ h_c$ (in.H_2O)	Experimental Pressure Drop h_π (in. H_2O)	Calculated Pressure Drop* h_π (in.H_2O)	Plate Pressure Drop $h_o = h_\pi - h_t - h_{av}$ (in. H_2O)
D-3	30.2	0.43	0.41	1.21	1.21	0.41
	29.9	0.42	0.41	1.21	1.20	0.42
	29.2	0.44	0.41	1.20	1.18	0.39
	28.5	0.47	0.41	1.20	1.16	0.36
	28.2	0.44	0.41	1.18	1.15	0.37
	27.5	0.46	0.41	1.18	1.14	0.35
	27.4	0.46	0.41	1.17	1.13	0.34
3/4" Weir	27.2	0.43	0.41	1.17	1.13	0.37
	26.6	0.46	0.41	1.17	1.11	0.34
	26.2	0.46	0.41	1.15	1.10	0.32
	25.8	0.47	0.41	1.16	1.09	0.32
	25.1	0.47	0.41	1.15	1.08	0.31
	24.8	0.49	0.41	1.18	Unstable	Unstable
	24.8	0.49	0.41	1.16	Unstable	Unstable
	23.6	0.44	0.41	1.18	Unstable	Unstable
	23.6	0.44	0.41	1.14	Unstable	Unstable

* Calculated using V_p

TABLE A III (Continued)

SUMMARIZED PRESSURE DROP DATA

LIQUID ON PLATE - NEGLIGIBLE WATER RATE

Run	Air Rate V_p (ft./sec.)	Hydrostatic Head h_{av} (in.H_2O)	Hydrostatic Head $0.46\ h_c$ (in.H_2O)	Experimental Pressure Drop h_{π} (in.H_2O)	Calculated Pressure Drop* h_{π} (in. H_2O)	Plate Pressure Drop $h_o \cong h_{\pi} - h_t - h_{av}$ (in.H_2O)
D-4	30.3	0.61	0.50	1.34	1.30	0.36
	29.2	0.59	0.50	1.33	1.27	0.37
	28.9	0.59	0.50	1.33	1.30	0.37
	28.2	0.59	0.50	1.31	1.27	0.35
1" Weir	27.6	0.59	0.50	1.30	1.26	0.34
	27.1	0.58	0.50	1.30	1.24	0.35
	26.7	0.58	0.50	1.30	1.23	0.35
	26.2	0.60	0.50	1.32	1.22	0.35
	25.8	0.58	0.50	1.31	1.18	0.36
	25.3	0.55	0.50	1.31	Unstable	Unstable
D-5	29.8	0.71	0.64	1.56	1.43	0.48
	29.6	0.68	0.64	1.49	1.42	0.44
1 1/4" Weir	29.2	0.69	0.64	1.48	1.41	0.42
	28.8	0.67	0.64	1.47	1.40	0.43
	28.6	0.67	0.64	1.47	1.39	0.43
	28.2	0.70	0.64	1.47	Unstable	Unstable

* Calculated using V_p

TABLE A IV

SUMMARIZED PRESSURE DROP DATA

LIQUID FLOWING ACROSS PLATE

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Bubbling Section Length N (in.)	Hydrostatic Head h_{av} (in.H_2O)	Hydrostatic Head 0.46 h_c (in.H_2O)	Experimental Pressure Drop h_π (in. H_2O)	Calculated Pressure Drop h_π (in. H_2O) A*	Calculated Pressure Drop h_π (in. H_2O) B*
E-1	30.9	7.1	59.50	0.31	0.38	1.10	1.20	1.21
	30.8	8.8	59.50	0.35	0.41	1.13	1.23	1.23
	30.7	10.4	59.25	0.36	0.42	1.16	1.23	1.24
	30.7	11.9	59.25	0.41	0.44	1.20	1.25	1.26
	30.6	13.8	59.00	0.44	0.46	1.23	1.27	1.28
	30.6	14.7	59.00	0.45	0.47	1.26	1.28	1.29
	30.6	16.4	58.75	0.49	0.49	1.29	1.30	1.32
	30.5	17.3	58.50	0.50	0.51	1.31	1.32	1.34
1/4" Weir	30.5	18.5	58.50	0.51	0.52	1.32	1.33	1.35
	30.5	19.6	58.25	0.53	0.53	1.34	1.34	1.36
	30.4	20.8	58.00	0.57	0.53	1.35	1.33	1.36
	30.4	21.4	57.75	0.57	0.54	1.37	1.34	1.38
	29.8	24.0	56.75	0.57	0.55	1.43	1.34	1.39

A* Calculated using V_p

B* Calculated using V_p
corrected for upstream fringe of inactive perforations.

TABLE A IV (Continued)

SUMMARIZED PRESSURE DROP DATA

LIQUID FLOWING ACROSS PLATE

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Bubbling Section Length N (in.)	Hydrostatic Head h_{av} (in.H_2O)	Hydrostatic Head 0.46 h_c (in.H_2O)	Experimental Pressure Drop h_π (in. H_2O)	Calculated Pressure Drop h_π (in. H_2O) A*	B*
E-2	30.6	5.8	59.50	0.38	0.44	1.17	1.25	1.26
	30.6	9.4	59.50	0.47	0.48	1.26	1.29	1.30
	30.6	11.6	59.25	0.52	0.52	1.31	1.33	1.34
	30.4	13.3	59.00	0.50	0.54	1.33	1.35	1.36
1/2" Weir	30.4	14.6	59.00	0.54	0.55	1.36	1.36	1.37
	30.4	15.6	58.75	0.57	0.56	1.38	1.37	1.38
	30.4	16.5	58.75	0.57	0.58	1.39	1.39	1.40
	30.4	18.0	58.50	0.62	0.59	1.41	1.40	1.42
	30.4	19.3	58.25	0.62	0.60	1.44	1.41	1.43
	30.2	21.5	57.75	0.65	0.63	1.47	1.43	1.46
E-3	30.4	6.7	59.25	0.55	0.58	1.34	1.39	1.40
	30.3	8.5	59.00	0.57	0.60	1.39	1.40	1.42
	30.2	11.1	58.50	0.62	0.64	1.45	1.44	1.46
	30.2	12.8	58.50	0.66	0.65	1.50	1.45	1.47
3/4" Weir	30.2	14.2	58.25	0.68	0.68	1.54	1.48	1.51
	30.1	15.5	58.00	0.69	0.69	1.56	1.49	1.52
	30.1	16.4	57.75	0.71	0.70	1.57	1.50	1.53
	30.0	18.0	57.50	0.73	0.72	1.62	1.51	1.55
	30.0	19.4	57.25	0.77	0.73	1.63	1.52	1.56
	29.8	21.5	57.00	0.79	0.76	1.72	1.55	1.59

A* Calculated using V_p

B* Calculated using V_p corrected for upstream fringe of inactive perforations.

TABLE A IV (Continued)

SUMMARIZED PRESSURE DROP DATA

LIQUID FLOWING ACROSS PLATE

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Bubbling Section Length N (in.)	Hydrostatic Head h_{av} (in. H_2O)	Hydrostatic Head 0.46 h_c (in. H_2O)	Experimental Pressure Drop h_π (in. H_2O)	Calculated Pressure Drop h_π (in. H_2O) A*	Calculated Pressure Drop h_π (in. H_2O) B*
E-4	30.5	6.8	59.00	0.65	0.67	1.51	1.48	1.49
	30.5	9.1	59.00	0.71	0.69	1.57	1.50	1.51
	30.4	11.6	58.50	0.73	0.73	1.63	1.54	1.56
	30.4	13.7	58.25	0.73	0.75	1.66	1.56	1.58
	30.2	14.2	58.25	0.72	0.77	1.69	1.57	1.60
1" Weir	30.2	15.6	58.00	0.76	0.78	1.71	1.58	1.62
	30.2	16.9	57.75	0.78	0.80	1.74	1.60	1.63
	30.0	18.3	57.50	0.80	0.81	1.76	1.60	1.64
	30.0	19.2	57.50	0.80	0.82	1.78	1.61	1.65
	30.0	20.4	57.00	0.85	0.84	1.82	1.63	1.68
	30.0	21.3	57.00	0.86	0.84	1.86	1.63	1.68
F-1	30.6	15.4	59.75	0.48	0.48	1.30	1.29	1.29
	29.7	15.3	59.00	0.48	0.48	1.28	1.27	1.28
	28.7	15.4	58.50	0.50	0.48	1.26	1.24	1.26
1/4" Weir	27.7	15.3	57.75	0.49	0.48	1.27	1.21	1.24
	26.5	15.2	57.00	0.47	0.47	1.29	1.17	1.21

A* Calculated using V_p

B* Calculated using V_p corrected for upstream fringe of inactive perforations.

TABLE A IV (Continued)

SUMMARIZED PRESSURE DROP DATA

LIQUID FLOWING ACROSS PLATE

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Bubbling Section Length N (in.)	Hydrostatic Head h_{av} (in.H_2O)	Hydrostatic Head 0.46 h_c (in.H_2O)	Experimental Pressure Drop h_π (in. H_2O)	Calculated Pressure Drop h_π (in. H_2O) A*	B*
F-2	30.5	14.4	59.50	0.55	0.55	1.37	1.36	1.37
	29.1	14.3	58.75	0.56	0.55	1.35	1.32	1.34
1/2" Weir	28.2	14.3	58.00	0.58	0.55	1.35	1.29	1.32
	27.1	14.2	57.25	0.56	0.55	1.37	1.27	1.30
	25.2	14.2	56.00	0.54	0.51	1.35	1.18	1.22
F-3	30.1	12.4	59.50	0.64	0.65	1.52	1.45	1.45
	29.1	12.8	58.75	0.66	0.65	1.49	1.42	1.44
3/4" Weir	28.3	12.6	58.00	0.66	0.65	1.48	1.40	1.42
	27.5	12.6	57.50	0.64	0.65	1.49	1.38	1.41
	26.2	12.5	56.75	0.65	0.60	1.50	1.29	1.33
F-4	30.3	11.5	59.50	0.70	0.73	1.61	1.53	1.54
	29.4	11.4	59.00	0.72	0.73	1.60	1.51	1.52
	28.2	11.4	58.00	0.76	0.72	1.59	1.46	1.49
1" Weir	27.2	11.4	57.25	0.71	0.69	1.67	1.41	1.44

A* Calculated using V_p

B* Calculated using V_p corrected for upstream fringe of inactive perforations.

TABLE A IV (Continued)

SUMMARIZED PRESSURE DROP DATA

LIQUID FLOWING ACROSS PLATE

Run	Air Rate V_p (ft./sec.)	Water Rate G' (gpm/ft.)	Bubbling Section Length N (in.)	Hydrostatic Head h_{av} (in.H_2O)	Hydrostatic Head 0.46 h_c (in.H_2O)	Experimental Pressure Drop h_π (in. H_2O)	Calculated Pressure Drop h_π (in. H_2O) A*	Calculated Pressure Drop h_π (in. H_2O) B*
G-1	54.4	0.0	30.00	0.22	0.79	1.97	2.06	
1 1/2" Weir (Half of Perforated area covered)	54.0	18.2	30.00	0.44	1.01	2.34	2.27	
	53.4	26.2	30.00	0.50	1.08	2.48	2.33	
	53.0	30.5	30.00	0.56	1.10	2.60	2.35	
	52.8	34.4	30.00	0.60	1.14	2.64	2.38	
	52.8	39.1	30.00	0.65	1.19	2.70	2.43	
	52.6	42.6	30.00	0.70	1.21	2.70	2.45	
	52.8	53.7	30.00	0.78	1.30	2.95	2.54	
H-1	57.4	33.1	30.00	0.52	1.15	2.72	2.48	
1 1/2" Weir (Half of Perforated area covered)	54.8	32.9	30.00	0.57	1.14	2.66	2.42	
	53.6	32.9	30.00	0.62	1.15	2.62	2.41	
	50.2	32.9	30.00	0.67	1.14	2.58	2.32	
	48.2	32.7	30.00	0.66	1.15	2.55	2.29	

A* Calculated using V_p

B* Calculated using V_p corrected for upstream fringe of inactive perforations.

A. Sample Calculations

Sample calculations will be carried through for two types of calculations:

1. Hydraulic Gradient Correlation
2. Pressure Drop Correlation

1. Hydraulic Gradient Correlation

Data from Run E-2 are used for the calculations following:

$$f' = \frac{2F\, g_c\, r_h}{V_f^{\,2}\, N} \qquad (1)$$

Where

$$F = \frac{\Delta h}{24} = \frac{0.22}{24} = 0.0092$$

$$g_c = 32.2 \text{ ft./sec.}^2$$

$$r_h = \frac{bL_c}{b + 2L_c} \qquad (2)$$

$$b = 1.125 \text{ ft.}$$

$$L_c = \frac{2h_c}{12} = \frac{2(1.22)}{12}$$

$$= 0.203 \text{ ft.}$$

$$r_h = \frac{1.125\ (0.203)}{1.125 + 2(0.203)} = 0.149 \text{ ft.}$$

$$V_f = \frac{G'}{(60)\ (7.46)\ L_c\bar{\Phi}} \qquad (3)$$

$$= \frac{15.6}{(60)\ (7.46)\ (0.203)\ (1/3)} = 0.516 \text{ ft./sec.}$$

$$N = 5.0 \text{ ft.}$$

$$f' = \frac{(2)\ (0.0092)\ (32.2)\ (0.149)}{(0.516)^2\ \ (5.0)}$$

$$= 0.0663$$

$$T = \frac{D_p}{h_c - D_p} \qquad (7)$$

$$= \frac{0.12}{1.22 - 0.12} = 0.109$$

$$f'T = 0.00723$$

$$Re' = \frac{r_h V_f \rho_f}{\mu_f} \qquad (4)$$

$$\rho_f = \rho_1 \Phi \qquad (5)$$

$$= \frac{62.4}{3} = 20.8 \text{ lb./ft.}^3$$

$$\mu_f = \mu_1 \Phi \qquad (6)$$

$$= \frac{0.000672}{3} = 0.000224 \text{ lb./ft.-sec.}$$

$$Re' = \frac{(0.149)\ (0.516)\ (20.8)}{(0.000224)}$$

$$= 7.14 \times 10^3$$

2. Pressure Drop Correlation

Data from Run E-2 are used in the following calculations:

$$V_p = \frac{Q_a P_s}{A_p P_a}$$

$$V_p = \frac{27.4 \times 423}{0.936 \times 407}$$

$$V_p = 30.5 \text{ ft./sec.}$$

$$h_t = \frac{0.04 \gamma}{\rho_1 D_p} \qquad (11)$$

$$h_t = \frac{0.04 \times 72.8}{62.4 \times 0.125}$$

$$h_t = 0.37 \text{ in. } H_2O$$

$$h_{\pi} = h_o + h_t + h_{av} \qquad (12)$$

$$h_o = 1.38 - 0.37 - 0.57$$

$$h_o = 0.44 \text{ in. } H_2O \text{ (experimental plate pressure drop)}$$

$$h_o = C\, V_p^{\,2} \qquad (10)$$

$$h_o = 0.00047\ (30.5)^2$$

$$h_o = 0.44 \text{ in. } H_2O \text{ (calculated plate pressure drop)}$$

B. Plate Leveling Procedure

The following procedure was employed to insure proper leveling of the perforated plate and zeroing of the manometer chart:

1. Hydrostatic head manometer lines to the taps in the inlet and exit calming sections were purged of air by forcing water through them from the taps.
2. The perforated area of the plate was blanked off with a piece of sheet metal.
3. An exit weir was installed and water run onto the plate. Water flow was adjusted to be just sufficient to maintain weir level. If leakage under the sheet metal was excessive, air was admitted to the air chamber to build up pressure and stop the leakage.
4. The liquid levels in the upstream and downstream calming sections were measured on the plate and if found unequal, the plate level was adjusted by leveling screws on the legs of the apparatus.

5. The manometer sheet was adjusted so that the manometers for the upstream and downstream calming sections both read the same, the reading being that measured on the plate.

Using this procedure, the plate ends could be leveled to within plus or minus 1 mm.

C. Calibration of Flowmeters

1. Water Rate Measurement

The orifice in the water line was calibrated by direct measurement. The globe valve in the water line was set, the system was allowed to come to equilibrium, and the water orifice manometer recorded while water was collected for a measured time interval. The water collected was weighed and the water rate calculated in gallons per minute. This procedure was repeated for various flow rates and the results plotted to obtain a curve of water rate vs. the water orifice manometer reading.

2. Air Rate Measurement

Pitot tube traverses were made across the air duct for several air rates. From these traverses, the air rates were determined by means of graphical integration. The results were used to check the validity of using the standard orifice equation for non-compressible flow. The use of this equation was found to be satisfactory using the experimental constant:

$$C = 0.66$$

A curve of air rate, in cubic feet per sec., vs. the air rate manometer reading was plotted using the orifice equation.

D. Nomenclature

A_p = Total perforation area (ft.^{2}).

A_s = Area of perforated section (ft.^{2}).

b = Plate width (ft.).

D_p = Perforation diameter (in.).

F = Friction head loss = $\frac{\Delta h}{24}$ (ft. of liquid).

f' = Modified friction factor = $\frac{2g_c r_h F}{V_f^2 N}$

G' = Volumetric flow rate (gpm/ft. of plate width).

g_c = Gravitational constant (32.2 ft. lbs. mass/sec.^{2} lbs. force).

Δh = Hydraulic Gradient across plate (in. of liquid).

h = Hydrostatic head (in. of liquid).

h_{av} = Average hydrostatic head in bubbling section (in. of liquid).

h_c = Downstream calming section hydrostatic head (in. of liquid).

h_o = Pressure drop through perforations (in. of liquid).

h_t = Pressure drop due to surface tension effects (in. of liquid).

h_{π} = Total plate pressure drop (in. of liquid).

L_c = Calculated foam height = $\frac{2 \times h_c}{12}$ (ft.).

N = Length of bubbling section (ft.).

P_a = Atmospheric pressure (in. of H_2O).

P_s = Static pressure upstream of air orifice (in. of H_2O).

Q_a = Volumetric flow rate of air (cfm).

r_h = Hydraulic radius (ft.).

Re' = Modified Reynolds number = $\frac{r_h V_f \rho_f}{\mu_f}$

T = Correlation factor = $\frac{D_p}{h_c - D_p}$

V_f = Foam velocity (ft./sec.).

V_p = Velocity of vapor based on total hole area (ft./sec.).

β = Factor in standard orifice equation. $\beta^4 = \left[\frac{A_p}{A_s}\right]^2$

γ = Surface tension of liquid (dynes/cm.).

μ_f = Foam viscosity (lb./ft. sec.).

μ_l = Liquid viscosity (lb./ft. sec.).

ρ_f = Foam density (lb./ft.^{3}).

ρ_l = Liquid density (lb./ft.^{3}).

ρ_v = Vapor density (lb./ft.^{3}).

Φ = Density factor = $\frac{\text{effective aerated density}}{\text{clear liquid density}}$

E. Literature Citations

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