Capacity Factors in the Performance of Perforated-plate Columns

Charles d'Ancona Hunt, D. N. Hanson, and C. R. Wilke
University of California, Berkeley, California

A study was made of factors affecting the vapor-handling capacity of perforated-plate liquid-vapor contacting columns. Vapor-phase pressure drop across plates, liquid entrainment upward from plate to plate, and plate stability were investigated as functions of operational and geometric column parameters.

Gas-phase pressure drop across dry perforated plates was observed to follow functional relationships predicted from available information for single perforations. The presence of liquid on a plate increased the total pressure drop by the equivalent clear-liquid head plus a small residue which is nearly constant for a given liquid.

Entrainment was observed to be a function of column gas velocity, independent of gas velocity in the perforations. Weight rate of entrainment was also found to be proportional to the gas density, independent of liquid density, and inversely proportional to the liquid-surface tension. For a given system, entrainment was observed to be proportional to approximately the third power of the group, gas velocity divided by the distance between the liquid surface and the plate above.

The stability of perforated plates was observed to be adequate for many industrial and experimental applications, as also reported in recently published studies, but contrary to qualitative statements found in the earlier literature. Stability was found to increase with decreasing perforation diameter and decreasing total perforation area relative to column cross-sectional area; to increase with greater gas density, liquid surface tension, and liquid wetting power; and to be virtually independent of liquid density and viscosity.

Operating limits of vapor and liquid throughput are shown for a typical application of perforated plates in liquid-vapor contacting columns.

The industrial use of perforated-plate columns for countercurrent contacting of liquids and vapors was until recently limited mainly to applications where the liquids contained large quantities of solid matter. According to general opinion on column design, the perforated-plate type of contacting unit had a narrow stable operating range of gas flow; whereas a bubble-cap unit had no particular lower limit of gas flow except at relatively high liquid flow rates.

Recent studies by Mayfield, Church, Green, Lee, and Rasmussen (*10*), and Arnold, Plank, and Schoenborn (*1*) show that the perforated-plate column has definite economic advantages over the bubble-cap plate column and that the possible range of gas and liquid flows for stable operating conditions is sufficiently wide for many applications in the chemical processing field. According to Mayfield *et al.* perforated-plate columns are being used by the **Celanese**

C. d'A. Hunt is at present with Stauffer Chemical Company, Richmond, California.

Corporation for most new applications, and existing bubble-cap plates are being replaced by perforated plates in many units.

The present work was undertaken prior to the appearance of references 10 and 1 in order to clear up questions arising from previous work in this department related to pressure drop and plate stability. Another objective was to study entrainment in the perforated-plate column in order to determine upper limits of gas flow rate in the column imposed by excessive entrainment upward from plate to plate of liquid droplets in the gas stream. The experimental work was done in a 6-in.-diam. column.

In columns with liquid flowing across the plate and over a weir, the liquid head on the plate in the stable operating region is determined not only by the height of the overflow weir and the head of liquid required for the flow over the weir but also by the degree of aeration of the liquid on the plate. This aeration is the result of the flow of gas through the body of liquid and is fairly independent of gas flow rate in the stable operating region. However, the phenomenon of aeration is little understood at this time, and the degree of aeration can at best be predicted within ±20%.

In order to eliminate a large share of this uncertainty in the study of pressure drop across perforated plates, the liquid head on the plate was maintained by means of a constant-head tank connected to the column just above the plate. The head was then measured by means of a pressure tap located at the plate level. In this way the effect of many variables upon pressure drop could be determined without any interference from changing aeration of the liquid on the plate. Actually the liquid head on the plate constitutes an important part of the total pressure drop for the gas flowing up the column; so a complete prediction of gas pressure drop requires an accurate knowledge not only of the the effect of the variables studied in this work but also of the degree of aeration.

Because of the unreliability of the performance of liquid overflow weirs in a 6-in.-diam. column this study does not include any information on the effect of liquid flow rates across perforated plates.

EXPERIMENTAL PROCEDURE APPARATUS

Pressure drop, entrainment, and stability criteria were studied in a 6-in.-diam. perforated-plate column, using a nonflow constant-head system to maintain liquid on the plate and a totally enclosed gas-circulation system to provide gas flow through the perforated plate.

A diagram of the experimental system is shown in Figure 1. Both the gas-circulation system and the liquid constant-head system were enclosed and vented to the column in order to allow the use of other gases and liquids besides air and water. Provision was made for purging of manometers in the plate system with the liquid in use. A heat exchanger cooled by tap water served to remove heat added from the work of compression of the gas-circulation blower. Since the orifice measured the flow of gas between the blower and the heat exchanger, gas properties at both the orifice and the plate were measured in order to avoid significant systematic errors in gas density determination. The orifice was assembled according to A.S.M.E. standard specifications.

Gas entered the column through a trap designed to prevent the liquid which dumped through the perforations from filling up the gas ducts, flowed through a set of straightening screens designed to provide a 15:1 improvement in flow distribution, and impinged upon primary plate. The column was constructed of 1/16-in.-thick wall brass with plastic windows provided for observation of plate action and dumping. Pressure taps 6 in. below and 18 in. above the plate were constructed to avoid any possibility of drops of liquid affecting the pressure reading.

The liquid entrained from the primary plate was collected on a similar plate higher in the column and drained continuously into a vented receiver which was calibrated for determination of the volume of the liquid entrained as a function of time. Less than 1% of the liquid reaching this upper plate could be further entrained out of the tapered, baffled column section above this plate. All entrainment data were taken under conditions which assured little or no dumping of liquid from the catcher plate to the primary plate. The plate spacing was increased by adding glass spacer sections to the column just below the entrainment catcher plate. After the completion of the pressure-drop measurements the metal portion of the column above the plate was shortened to 8 in. in order to allow the determination of entrainment at small plate spacings.

The gas pressure at the entrance to the blower was maintained at slightly greater than atmospheric pressure in order to prevent inleakage of air in runs using other gases and to prevent excessive leakage of these gases through the inadequate seal around the blower shaft. Gas-flow velocity was controlled by means of a simple slide valve in the 4-in. ducting used throughout the remainder of the system. Liquid head on the plate was maintained constant within 0.3 in. by means of the adjustable overflow weir in the constant-head tank. The liquid was continuously circulated from a storage tank through the constant-head tank.

The manometers connected to the column and plate were assembled with glass and transparent plastic tubing in order to make visible any gas bubbles in lines which should have been full of liquid. The manometers were ¾ in. in diameter and vertical and could be read to 0.02 in. of water. The pressure drop at the orifice was

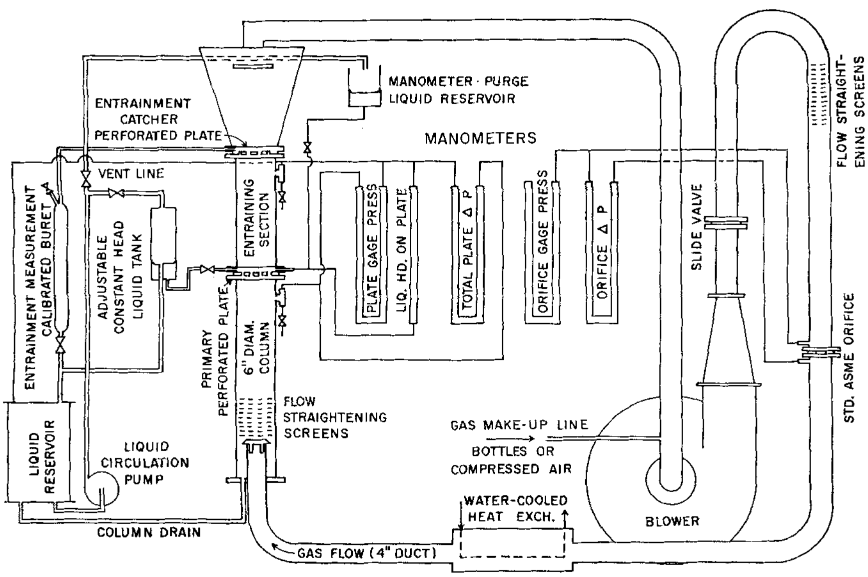

Fig. 1. Schematic diagram of experimental equipment.

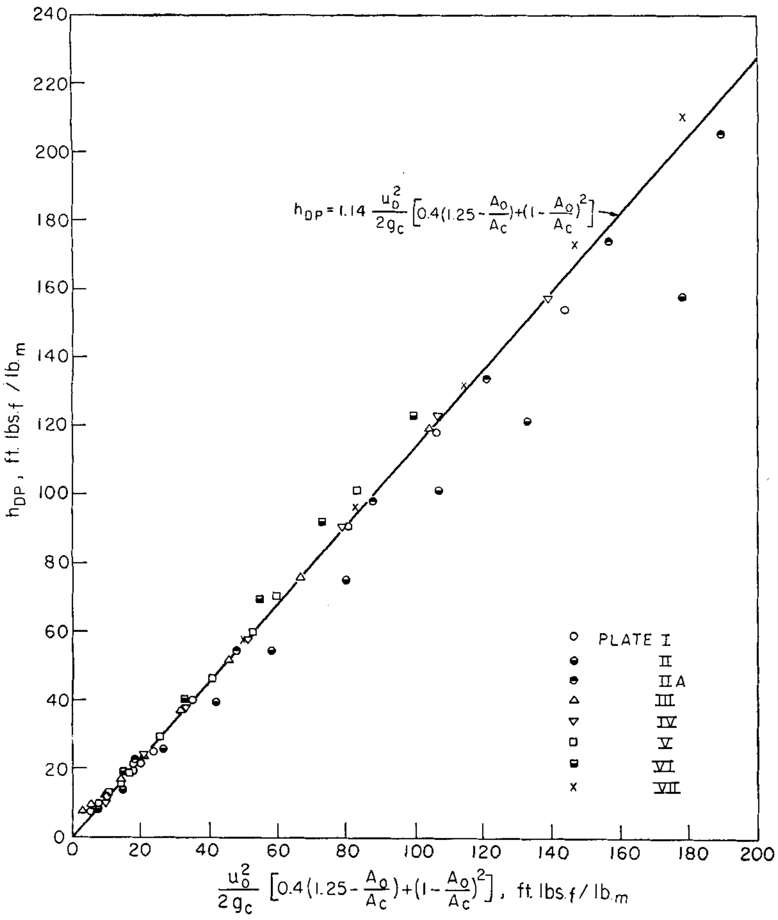

Fig. 2. Pressure drop for flow of air through dry plates.

TABLE 1.—CONFIGURATION OF PERFORATED PLATES

(All holes in equilateral triangular spacing)

Plate	Thickness, in.	Hole diam., in.	Hole spacing, in.	Number of holes	Area per hole, sq. ft.	Total hole area, sq. ft.	Percentage of total column area
I	⅛	⅛	¼	433	0.0000852	0.0369	18.8
II	⅛	⅛	½	109	0.0000852	0.00929	4.9
III	¼	¼	1	31	0.000341	0.01056	5.4
IV	¼	¼	½	109	0.000341	0.0372	19.0
V	½	½	2	7	0.00136	0.00954	4.9
VI	½	½	1	31	0.00136	0.04226	21.5
VII	⅜	⅜	1½	13	0.000767	0.00997	5.1
VIII	¼	¼	¾	55	0.000341	0.0187	9.5
II*A*	⅛	⅛	½	109	0.0000852	0.00929	4.9

measured with a standard Uehling inclined manometer.

Gas temperatures were measured with thermocouples immersed in the gas stream.

Plates of 20% relative perforation area were so unstable with respect to dumping that stabilizing screens had to be installed above these plates in order that a suitable liquid head might be maintained. The stabilizer consisted of three concentric cylinders, about 6 in. long, composed of 1/16-in. gauge wire woven into a ¼-in. mesh screen. The stabilizer had no effect on pressure-drop measurements.

The trays used in the experiments are listed in Table 1. After reaming, micrometer measurements on the holes indicated the diameter to be within 0.001 in. of the nominal diameter.

Properties of the liquids used are listed on Figure 7.

Dry-plate Pressure Drop

Data on the pressure drop for gas flowing through perforated plates set in ducts were taken by both Arnold *et al.*(*1*) and Mayfield *et al.*(*10*). Arnold used relatively thin plates uniformly 0.029 in. thick with perforation diameters from 0.039 to 0.376 in. Mayfield used thicker plates, from ⅛ to ¼ in., with perforations also from ⅛ to ¼ in. Both investigators employed a simplified orifice equation to represent their data.

The plates used by Arnold *et al.* approximate sharp-edged orifices. It might be expected that the orifice coefficient obtained would be a function of Reynolds number, and this is borne out by the fact that Arnold found his pressure drop to be proportional to the 1.8 power of velocity through the perforations, rather than to the power 2, which would be required if the discharge coefficient were constant. On the other hand the plates used by Mayfield *et al.* approximate short tubes rather than sharp-edged orifices, and their data were correlated by use of the square of the velocity. Neither group of investigators generalized their correlation with plate geometry.

In preliminary studies Claypool (*4*) found that pressure drop through perforated plates with a single hole was correlated by the orifice relation if the ratio t/D_o, the plate thickness to the perforation diameter, were 0.9 or greater. The plates used by Mayfield *et al.* conform to this criterion with only one exception, where the ratio t/D_o was 0.67. It would be expected that the plates used in industrial practice would be relatively thick, to provide adequate mechanical strength and to ensure long freedom from the effects of corrosion. Accordingly, in the present study the ratio of t/D_o was held equal to unity, and plate thicknesses ranged from ⅛ to ½ in.

The pressure drop through a short tube running full may be interpreted as the sum of an entrance loss and an exit loss. For perforations with sharp edges at both entrance and exit this would be

$$h=\frac{u_o^2}{2g_c}\left[0.4\left(1.25-\frac{A_o}{A_c}\right)+\left(1-\frac{A_o}{A_c}\right)^2\right] \quad (1)$$

where

h = head loss, ft. lb. force/lb. mass

u_o = velocity through the perforation, ft./sec.

g_c = 32.2 lb. mass.(ft.)/lb. force (sec.)^2

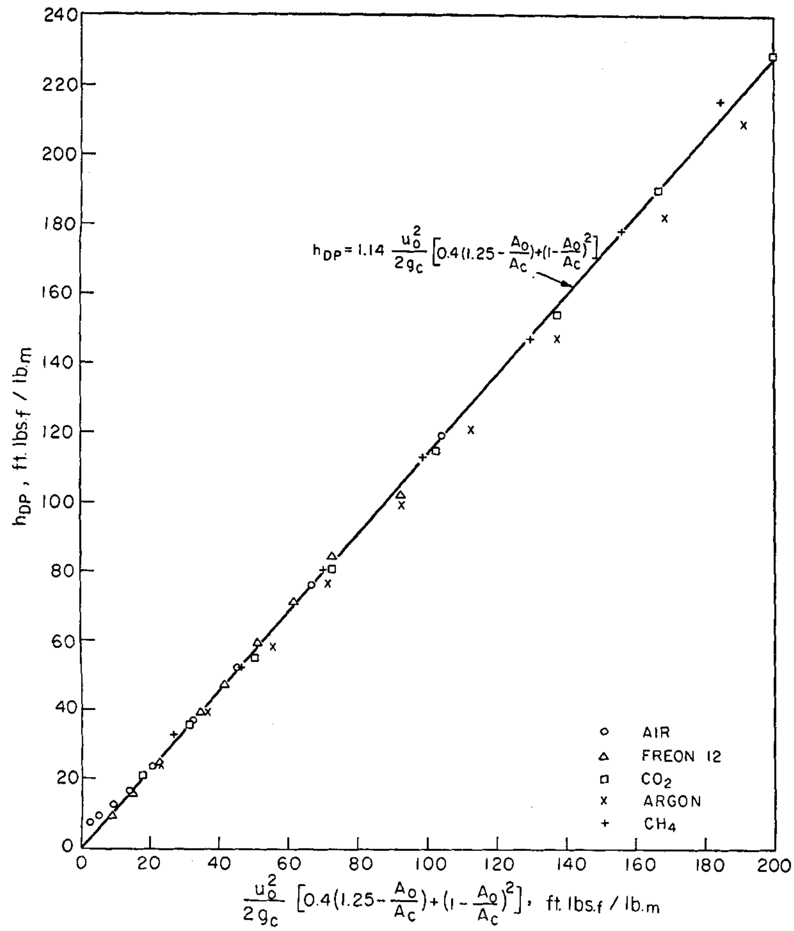

Fig. 3. Pressure drop for flow of various gases through dry plate; plate III.

A_o = total perforation area, sq.ft.
A_c = area of column available for gas flow, sq.ft.

Equation (1) is correct for circularly symmetric sudden enlargements and contractions but is not necessarily correct for perforated plates in ducts; however, studies by Baines and Petersen(*3*) on perforated plates composed of sharp-edged orifices in ducts have shown that flow through such plates can be correlated by the ordinary orifice relation, and it is reasonable to expect correlation of pressure drop for thick perforated plates by some relation like Equation (1).

The pressure drop for flow of air through plates I through VII, a range of perforation diameters from ⅛ to ½ in. and of A_o/A_c from 0.05 to 0.20, is shown in Figure 2. With one exception, plate II, the data are represented by Equation (2) within a few per cent.

$$h_{DP} = 1.14\frac{u_o^2}{2g_c}\left[0.4\left(1.25-\frac{A_o}{A_c}\right)+\left(1-\frac{A_o}{A_c}\right)^2\right] \qquad (2)$$

Plate VI deviates from Equation (2) by +8%, the maximum deviaion with the exception of plate II, which deviates by —18%. These deviations are attributable to defective drilling of the perforations. Plate II was the first plate made, and in the operation of reaming the holes to size, the plate was not rigidly clamped. All other plates were clamped during this operation. After the pressure-drop data were taken and the deviation of this plate was seen, a second plate, II*A*, was made exactly like plate II with the plate clamped during final reaming. It can be seen that plate II*A* is essentially on the line given by Equation (2).

Gases other than air were also used: Freon 12, carbon dioxide, argon, and methane. The data for these gases are shown in Figure 3, and it can be seen that Equation (2) holds within a few per cent. From these results it is felt that Equation (2) will accurately represent the dry-plate pressure drop for any gas flowing through a plate made up of sharp-edged holes on triangular centers for which the ratio of t/D_o is 0.9 or greater and will probably be adequate for $t/D_o = 0.67$. From the form of Equation (2) it might be expected that the pressure drop for commercial punched trays would be lower than that found here. The punching process will break the edge of the hole, and if this edge is used as the upstream edge a radius of curvature as low as 0.14 D_o will reduce the entrance loss effectively to zero and reduce the total loss by about one third(*12*).

The data of Mayfield *et al.* for all plates investigated in their 6-in. column fall approximately 14% below the values predicted by Equation (2), or essentially in accord with the theoretical values of entrance and exit loss. This difference may well be due to minor variations in hole size due to different methods of manufacture. Data from their large column are as much as 30% higher than Equation (2).

Jones and Pyle(*9*) report a curve of dry-plate pressure drop vs. *F* factor based on hole velocity for an 18-in. column with ⅛-in.-diam. holes. Equation (2), applied to their column specifications, gives dry-plate pressure drops approximately 25% lower than those represented by their curve. Their higher pressure drops are believed due to use of thin plates which approximate sharp-edged orifices. The data of Arnold *et al.*, also for thin plates, roughly agree with those of Jones and Pyle.

Wet-plate Pressure Drop

The presence of liquid on a perforated plate creates a static head of pressure at the plate surface which must be added to the other pressure drops experienced by the gas. The action of the bubbling gas aerates the liquid(*1, 7, 10*) to an extent dependent primarily on the liquid height. If liquid level on the tray is maintained by flow over a weir, the clear-liquid head equivalent to the aerated liquid is a function of weir height and liquid flow rate(*10*). No attempt was made in the present work to determine the degree of aeration. The liquid seal was maintained by a constant-head tank to counteract changes in head with change in gas flow. This aerated liquid head was measured in a manometer as equivalent clear liquid and subtracted from the total pressure drop. Essentially the same experiment was performed by Arnold *et al.* for one plate with air and water and by Mayfield *et al.* for one plate with air and three liquids.

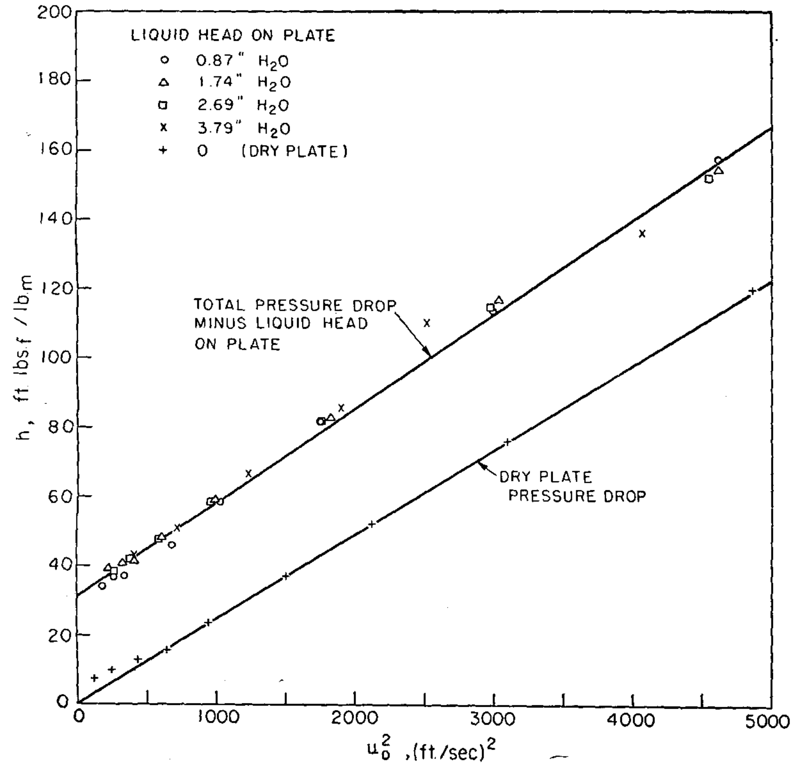

Fig. 4. Pressure drop with liquid on plate; air-water; plate III.

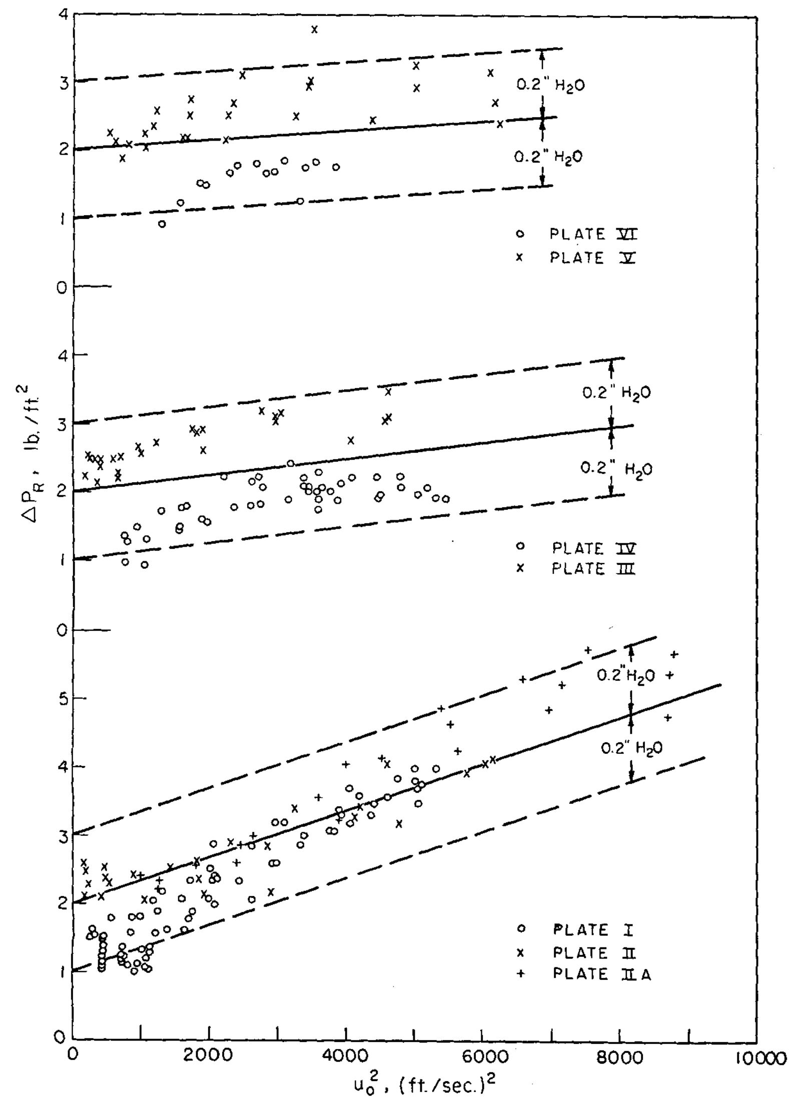

Fig. 5. Residual pressure drop with various plates; air-water.

The turbulent-expansion loss for gas flow across a dry plate would probably be little changed by the presence of liquid on the plate. Hence the total pressure drop for gas flow across a plate with liquid present would be expected to be at least as great as the sum of the equivalent clear-liquid seal and the dry-plate pressure drop. If a significant amount of energy is expended in the formation of bubbles, a corresponding additional pressure drop will be found.

In their experiments Arnold *et al.* found that the residual pressure drop unaccounted for by the sum of dry-plate drop and liquid seal was approximately 10% of the total drop, ranging from 0.1 in. of water to 0.5 in. Mayfield *et al.* found the residual to range from 0 to 0.2 in. of water and decided that it was insignificant in practical design.

In the present work the total pressure drop was measured for the system air-water for plates I through VI. In order to determine the effect of different gases and liquids total pressure drop was measured with plate III and water for all the gases used in the dry-plate experiments and with the air and the liquids listed in Figure 7.

The results of the air-water experiments with plate III are shown in Figure 4. The data for various liquid heads on the tray are shown. Liquid head was varied from 0.87 to 3.79 in. of water. The data obtained scatter at random around the line drawn for total drop minus liquid head. A similar scatter was obtained for all plates tested, leading to the conclusion that there is a residual pressure above that which can be accounted for by dry-plate drop plus liquid head, which is independent of values of liquid head normally encountered.

The residual pressure drop ΔP_R, defined as the total pressure drop minus the equivalent liquid head minus the dry-plate pressure drop, is shown in Figure 5 for all the plates investigated. In the calculation of these residual pressure drops, the best lines through the dry-plate pressure-drop data for the individual plates were used in order to obtain as much accuracy as possible in the residual. The residual pressure drop is small in all instances, reaching a maximum value of about 5 lb./sq.ft., or 1 in. of water with plate II, a plate with ⅛-in. perforations on 4 D_o spacing. The residual appears to increase with increasing gas velocity, more so with ⅛-in. perforations and less with larger perforations. The residual also appears to be consistently higher for plates with the perforations spaced on $4D_o$ than for those with $2D_o$ spacing. There is little apparent difference in the residual pressure drop extrapolated to zero gas velocity for the various plates, the extrapolated residual being about 2 lb./sq.ft. or 0.4 in. of water for all the plates.

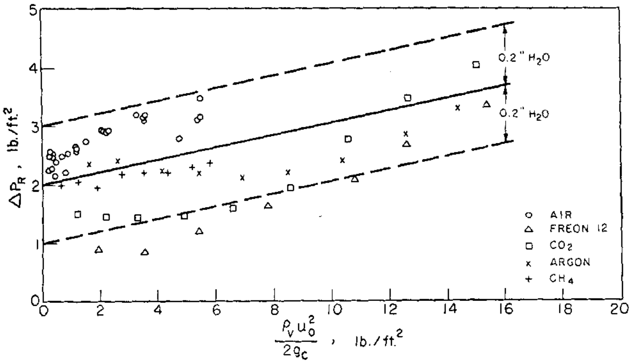

Fig. 6. Residual pressure drop with various gases and water; plate III.

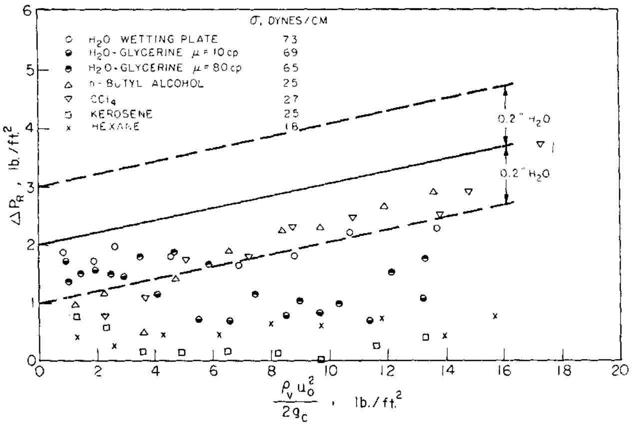

Fig. 7. Residual pressure drop with air and various liquids; plate III.

The residual pressure drop for various gases with water is shown in Figure 6. The data were all taken with plate III. The residual pressure-drop data correlate more satisfactorily as a function of the kinetic energy of the gas rather than as a function of gas velocity alone. The lines drawn on Figure 5 for air-water and for the same plate are redrawn on Figure 6, and it is apparent that the data for various gases are essentially within the same limits of scatter as the data on air-water.

Data were also taken with plate III for air with various liquids. Viscosity was varied from 1 to 80 centipoises, specific gravity from 0.67 to 1.60, and surface tension from 73 to 18 dynes/cm. The data as presented in Figure 7 show no consistent trend in the residual pressure drop with any of these variables. However, qualitatively it appears that systems with lower surface tension give lower residual pressure drops, as will be noted in comparing the data with the lines for the system air-water, which are also drawn on the figure.

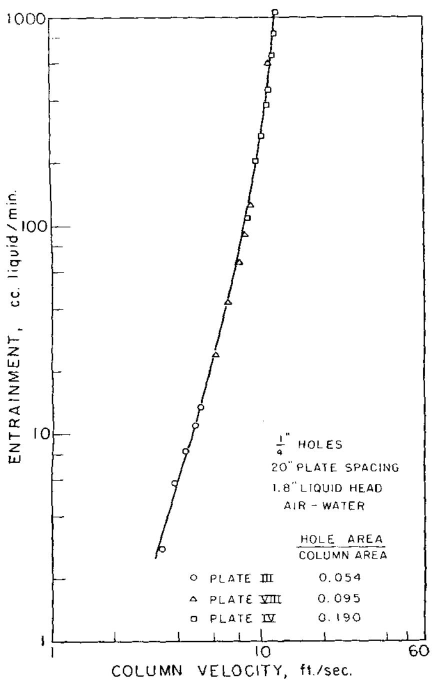

Fig. 8. Effect of velocity on entrainment.

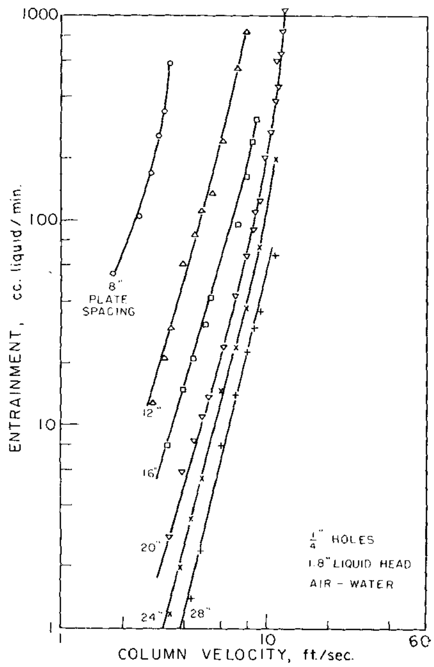

Fig. 9. Effect of plate spacing on entrainment.

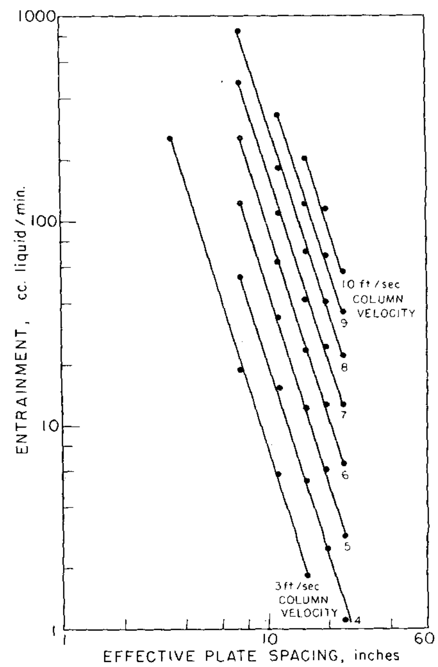

Fig. 10. Determination of relationship between effective plate spacing and entrainment.

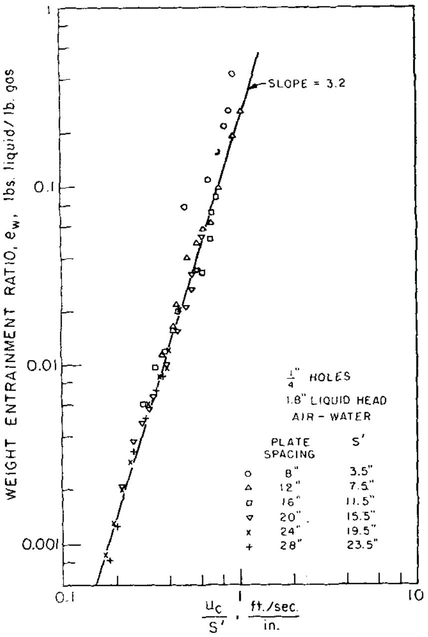

Fig. 11. Correlation of entrainment with column velocity and effective plate spacing.

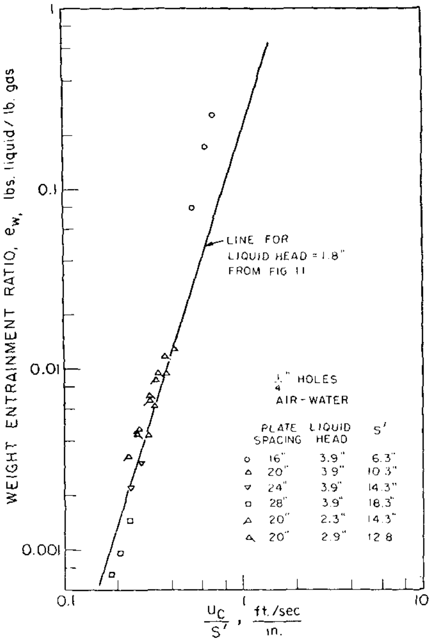

Fig. 12. Correlation of entrainment at various liquid heads.

Attempts to rationalize the residual-pressure-drop data with bubble formation have not been successful.

For practical design, in view of other uncertainties, the slight differences found in the residual pressure drop can probably be neglected. A constant residual of 2.5 lb./sq.ft. (0.5 in. of water) can be assumed, independent of velocity, plate geometry, and system, with a maximum error of approximately 0.5 in. of water over the entire range of variables investigated.

Entrainment

The entrainment of liquid drops by the rising gas was measured first with air and water in order to determine what geometrical factors were important. Previous investigations with bubble-cap plates (*2, 8, 11*) have shown slot velocity, column velocity, and plate spacing all to enter into the determination of the amount of entrainment.

The effect of hole velocity was *investigated* by the use of three ¼-in.-hole plates, plates with ratios of hole area to column area varying from 0.049 to 0.190. In all these runs the plate spacing was maintained at 20 in. and liquid head on the plate was held at 1.8 in. The data are shown on Figure 8 plotted vs. column velocity, and it is apparent from the fact that overlapping data at widely different hole velocities fall on the same curve that the entrainment is independent of hole velocity; for example, data taken at a column velocity of approximately 9 ft./sec. show the same entrainment although the hole velocities were as different as 95 ft./sec.. and 47 ft./sec. Data were also taken with ¼-in. hole plates at other values of plate spacing, again with liquid head held constant at 1.8 in. These data are shown on Figure 9 and indicate that entrainment is sharply dependent on plate spacing as well as column velocity, increasing exponentially with diminished plate spacing and increased column velocity.

It seemed intuitively correct that, barring a change in the character of the bubbling surface of aerated liquid with change in liquid depth, the entrainment should be a function of the distance between the bubbling surface and the plate above, i.e., the "effective plate spacing," and independent of the plate spacing itself. Unfortunately it was not possible to determine visually the foam height in the column used in order to calculate this effective plate spacing. Accordingly, runs were also made in which the liquid head was varied with and without variation in the plate spacing. From the results of these experiments it appeared that the foam density was between one third and one half of the true liquid density, independent of the gas velocity. An average value of 0.4 was assumed to hold for purposes of correlation. This value agrees well with the measurements of Bagnoli as reported by Gerster, Bonnet, and Hess(*7*), who found foam densities of 0.3 to 0.35 with air and water on plates with ⅛-in. holes. Bagnoli also found little or no effect of gas velocity. A more exact measurement of foam density is certainly desirable, but for purposes of determining entrainment at common plate spacings, the placement of the bubbling surface within 1 or 2 in. is *sufficiently* accurate. From the results of the work reported here the assumption of a density of 0.4 is within this accuracy.

The data of Figure 9 are cross-plotted on Figure 10 vs. effective plate spacing with column velocity as a parameter. Straight lines were obtained showing entrainment to be inversely proportional to the 3.2 power of the effective plate spacing, *S'*.

It might be noted that the straightness of the lines and the constancy of their slope lends support to the assumed foam density of 0.4 even though there is no reason *per se* to expect the entrain-

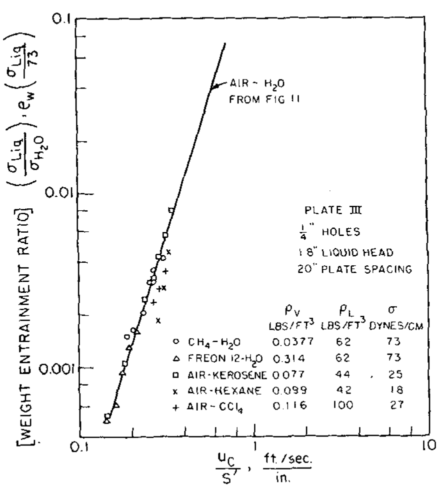

Fig. 13. Correlation of entrainment with various gases and liquids.

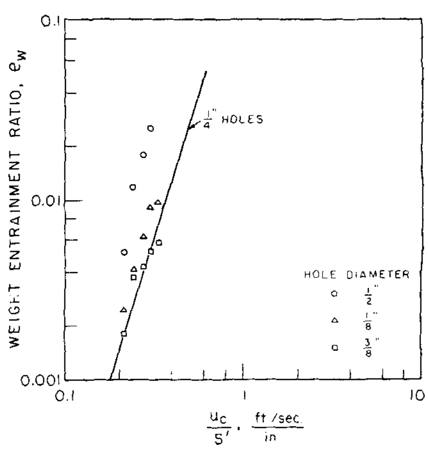

Fig. 14. Entrainment with varying perforation size.

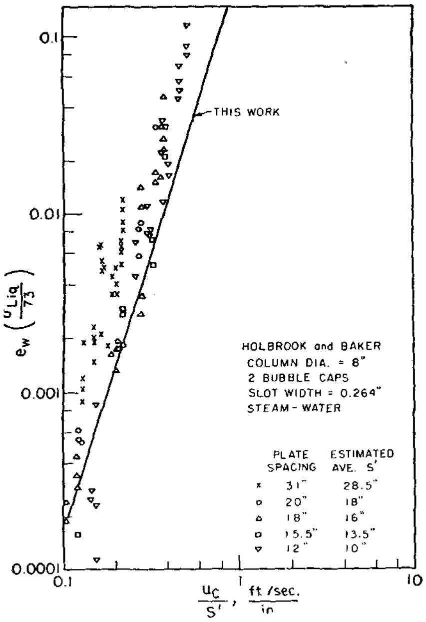

Fig. 15. Comparison of entrainment correlation with data of Holbrook and Baker.

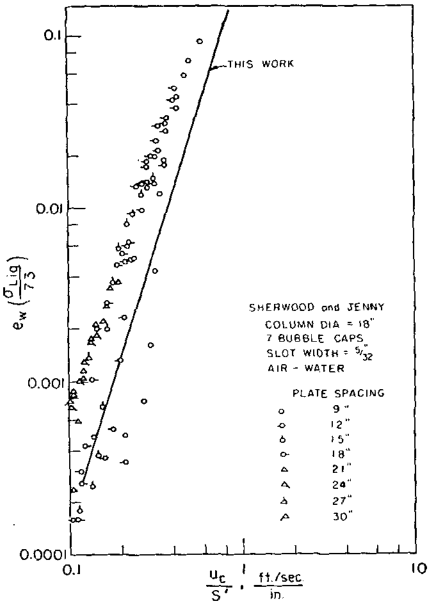

Fig. 16. Comparison of entrainment correlation with data of Sherwood and Jenny for bubble caps.

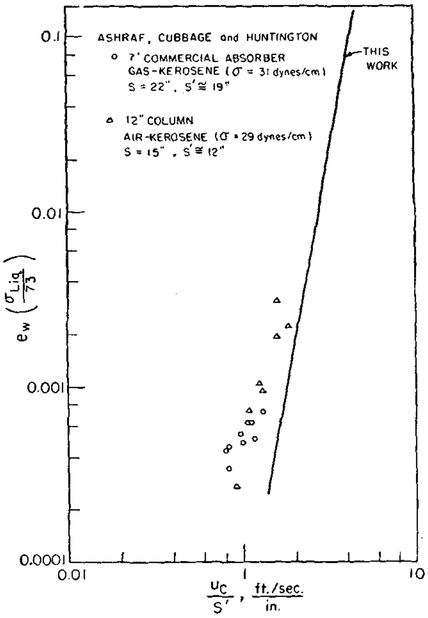

Fig. 17. Comparison of entrainment correlation with data of Ashraf *et al.* for bubble caps.

ment to be so simply related to the effective plate spacing.

Further data with other gases and liquids indicated that the weight entrainment ratio, pounds of liquid/pound of gas, was the proper variable to consider. It was found that adequate and simplified correlation could be obtained by plotting weight-entrainment ratio, e_w, vs. u_c/S'. From Figure 11 it can be seen that the correlation is satisfactory though limited to column velocities under 10 ft./sec., except for the data taken at 8-in. plate spacing, which are uniformly high. However, since the calculated effective plate spacing here is only 3.5 in., it would be expected that a small error in the location of the bubbling surface would have a large effect. To move the data for 8-in. spacing to the correlating line would require only the assumption of a foam density of 0.37 instead of 0.4.

The data at other values of liquid head are plotted vs. u_c/S' on Figure 12, and again except for the lowest effective plate spacing the correlation is adequate.

Data were also taken with water and the gases methane and Freon 12 and with air and the liquids kerosene, carbon tetrachloride, and hexane and are correlated on Figure 13. The data on other gases are seen to correlate well, indicating that the weight entrainment ratio is independent of the gas density. The data for other liquids deviate widely from the correlation if e_w is plotted vs. u_c/S'. However it was found that they correlate well if the ordinate is $e_w(\sigma_{liq}/\sigma_{H_2O})$ or $e_w(\sigma_{liq}/73)$ where σ_{liq} is the surface tension of the liquid on the plate in dynes/cm. It will be noted on Figure 13 that the data for kerosene are in excellent agreement, whereas the data for carbon tetrachloride and hexane are both low. The data for the latter two liquids are in some doubt because of evaporation losses from the entrainment collection plate. Although the gas circulation system was closed, leakage did occur and it was possible to estimate the evaporation losses only crudely. This problem was not present with kerosene owing to its low volatility.

A limited number of data for plates with other hole sizes were taken and are shown in Figure 14. The data for plates with ⅛-in. and ⅜-in. holes are seen to agree reasonably well with the correlation for ¼-in. holes, but the data for ½-in. holes are high. Visual observation of the bubbling surface of plates with ½-in holes indicated a higher degree of irregular splashing than was observed with the other hole sizes, and the higher entrainment is probably due to this effect. It is believed that the correlation obtained for ¼-in. holes will give satisfactory values for both ⅛- and ⅜-in. plates. The general correlation for weight entrainment ratio in pounds of liquid /pound of gas may be expressed by

$$e_w = 0.22\left(\frac{73}{\sigma_{liq}}\right)\left(\frac{u_c}{S'}\right)^{3.2}$$

where u_c is column velocity in feet/second and S' is effective plate spacing in inches, calculated as S, the actual plate spacing, minus 2.5 h_L, where h_L is the head of liquid on the tray in the bubbling zone expressed as inches of clear liquid.

Entrainment is apparently due primarily to splashing from wave action and/or the violent rupture of large bubbles at the top of the foam. High-speed photographs were made of the entrainment at a height of 20 in. above the lower plate, in addition to visual observations. In both observations large drops, up to ¼ in. in diameter, were observed to be thrown upward to at least this height. Counting the drops in the photographs showed that drops of about 0.2 in. comprised about 75% of the liquid visible in the photograph. At the same time the maximum size of drop which would be carried up by drag would be about 0.03 in. The marked dependence of entrainment on plate spacing also indicates that drag is unimportant.

Jones and Pyle(*9*) also determined entrainment for their sieve tray in distillation of acetic acid–water. Exact comparison of the present entrainment results with their data is not possible, as concentrations of the solutions were not given. If it is assumed that dilute aqueous solutions were used, the entrainment data are in substantial agreement.

Entrainment with bubble-cap plates has been studied at some length, notably by Holbrook and Baker(*8*), Sherwood and Jenny

(*11*), and **Ashraf, Cubbage, and** Huntington(*2*). Qualitative observations by Mayfield *et al.*(*10*) indicated that jetting and splashing were more severe with bubble caps than with perforated plates with resultant higher visual entrainment. The results of the three experimental studies are shown in Figures 15, 16, and 17 compared with the results of the present study. Foam heights were difficult to determine from the reported data, but it is believed the estimates made are accurate within about 2 in. The data of Holbrook and Baker scatter but are seen to have the same trend as the present data with column velocity. The effect of plate spacing appears to be smaller than found here. The precise data of Sherwood and Jenny show a varying effect of column velocity which is roughly the same as that found with perforated plates. Entrainment is found to be about three times higher with bubble caps. When cross-plotted vs. S' at column velocities of 2 and 3 ft./sec. the data give straight lines of slope minus 3.1, almost exactly those found with perforated plates. The data of Ashraf *et al.* are of interest because they were obtained with kerosene as the liquid and include data on a 7-ft. diam. commercial absorber. Again they are higher by about a factor of 5 than the data obtained with perforated plates.

The effect of entrainment on plate efficiency has been derived by Colburn(*5*), who established the relationship describing entrainment which will give minimum column cost for any particular flows. Using the exponential relation found here and assuming the molal entrainment ratio equal to the weight entrainment ratio (roughly true for distillation columns) give this relation as

$$\left(e_w\right)_{opt} = \frac{L/V}{2E}$$

where L and V are liquid and vapor flows in moles and E is the Murphree vapor efficiency. As Colburn pointed out, the optimum entrainment is high. For example, for $L/V = 0.8$, $E = 0.8$, $(e_w)_{opt} = 0.5$ lb. liquid/lb. vapor. Such entrainments were not reached in the present study at plate spacings of 20 in. or more even at velocities of 10 ft./sec. in the column, and it is believed that entrainment is not a limiting capacity factor in ordinary columns, rather that excessive pressure drop will cause the column to flood before entrainment becomes seriously large.

Plate Stability

Stability of the plates with respect to liquid dumping was studied by measuring the quantity of liquid draining through the holes. Measurements were made for all the plates with varying gas velocity and liquid head. With a given plate and liquid head it was found that the rate of dumping increased first slowly as gas velocity decreased and then more and more rapidly, giving curves with more or less sharp breaks when plotted as dumping rate vs. gas velocity. For low liquid heads and widely spaced perforations very distinct breaks were found, indicating a lower limit to vapor velocity, i.e., "critical velocity," below which excessive liquid drainage would begin. At higher heads the breaks were less sharp, and at the lower values of hole spacing, specifically $2D_o$, dumping was found to be a smoothly ascending function of decreasing velocity, with considerable dumping going on at even moderate velocities. In Table 2 the critical velocities found for the various plates with air-water are recorded. The critical velocities in the perforations, calculated from the gas flow assuming all holes to be bubbling, are seen to increase in general as hole diameter increases. Plate *V*, with ½-in. holes spaced 4 D_o is an exception, showing greater stability than the corresponding 4 D_o ¼-in. hole plate. This discrepancy is believed to result from the fact that with this plate no holes were near the walls. A second plate, with ½-in. holes spaced on 6 D_o triangles, where some of the holes were as close as ½ in. to the wall, showed a critical velocity of 35 ft./sec., which is in line with the general trend. From the data obtained it appears that holes spaced 3 or 4 D_o apart give stable trays but that holes spaced on 2 D_o triangles are too unstable for general use except perhaps with holes as small as ⅛ in. diam.

Data at various liquid heads are shown in Table 3. Only the plates with holes spaced 3 D_o and 4 D_o are included, since the dumping found with the 2 D_o plates was high and the critical velocity was uncertain. The critical velocity is seen

TABLE 2.—PLATE STABILITY DATA

(1.8-in. liquid head)

Plate	Hole diam., in.	Hole spacing, in.	Gas	Liquid	Calculated critical gas velocity in holes, ft./sec.
I	⅛	¼	Air	Water	35
II	⅛	½	Air	Water	25
III	¼	1	Air	Water	30
IV	¼	½	Air	Water	>50
V	½	2	Air	Water	27
VI	½	1	Air	Water	>60
VIII	¼	¾	Air	Water	40
III	¼	1	Air	Water (wetting plate)	21
III	¼	1	Air	Water = glycerine ($\mu = 80$ centipoises)	21
III	¼	1	Air	Water = glycerine ($\mu = 10$ centipoises)	21
III	¼	1	Air	*n*-Butyl alcohol	23
III	¼	1	Air	Carbon tetrachloride	24
III	¼	1	Air	Kerosene	15
III	¼	1	Air	*n*-Hexane	14
III	¼	1	Freon 12	Water	15
III	¼	1	Methane	Water	32

TABLE 3.—PLATE STABILITY DATA, VARYING LIQUID HEAD, AIR-WATER

Plate	Hole diam., in., and spacing, in.	Calculated critical gas velocity in holes, ft./sec. $h_L = 1.0$ in.	$h_L = 1.8$ in.	$h_L = 2.8$ in.	$h_L = 3.8$ in.
II	⅛×4 D_o	5	25	32	35
III	¼×4 D_o	20	30	45	55
VIII	¼×3 D_o	27	40	55	70
V	½×4 D_o	25	27	27	30
V (modified)	½×6 D	30	35	40	45

to increase with increased head on the plate although the data scatter sufficiently that a functional relationship cannot be determined.

It is apparent from consideration of the data in Tables 3 and 4 that the stability is not markedly different for different hole sizes and that smaller holes do not in themselves contribute much greater stability to the plate. This is confirmed by Arnold, who found the minimum hole velocity to be substantially independent of hole size, being approximately 40 ft./sec. when hole spacing was about 4 D_o and about 30 ft./sec. when hole spacing was 3 D_o. They found little trend with weir height and liquid flow, but as pointed out by Mayfield the head of liquid in the bubbling zone is somewhat independent of these variables. Mayfield correlated data for stability of plates with 3/16-in. holes with dry-plate pressure drop. Their values are in the same region as those of this work and show the same trend with liquid head.

Data were also taken with plate III (¼ in. × 4 D_o) and various liquids and gases. From the data with Freon and water it appears that the gas-pressure drop in the holes is actually the important parameter. This conclusion was not completely borne out by the data on methane. However, operating data on commercial hydrocarbon columns reported by Eld(*6*) indicate satisfactory operation at velocities from 4 to 13 ft./sec. in the holes, with plates having up to 37% free area. These results are consistent with use of gas-pressure drop, which would be a function of ρv_o^2, as the correct criterion of stability.

Data taken across a variety of liquid properties indicate little or no effect of viscosity and density but some effect of surface properties. From rough measurements of the wettability of the liquids on the plates, the stability appears to increase with increased wettability. Kerosene and hexane are very effective in wetting the plate, carbon tetrachloride and butyl alcohol next, and water with various amounts of glycerol somewhat effective compared to pure water. In all cases the stability was increased over that with water, and so the use of critical velocities based on air-water pressure drops should be conservative.

APPLICATION TO COLUMN DESIGN

The relations found in this work can be used in the design of operating columns. For this it is convenient to work the relations into charts which enable the designer to estimate quickly the size of the column; an example of such a chart is shown in Figure 18. The superficial vapor velocity, in feet/second, based on the cross section of the empty column shell, is plotted vs. liquid flow, gallons/minute/foot of column diameter. Lines corresponding to flooding and to minimum vapor flow for stability are shown. These operating limits are determined chiefly by vapor flow although they are affected to some extent by liquid flow. Maximum and minimum liquid flows are shown as those giving calculated heads over the weir of 3 and 0.5 in. respectively, the normal range of bubble-cap trays.

Because of the number of variables which affect the operating limits of a column, it is necessary to set arbitrarily a considerable number of these variables in order to obtain easily usable charts. In the construction of Figure 18 the variables set were

Plate spacing $= S = 24$ in.
Perforations: ¼-in. D_o spaced on 3 D_o equilateral triangles
Angle subtended at the center by the weir $= 105°$
Weir height $= H_w = 1.5$ in.
Minimum downcomer clearance at bottom $= H_d = 2.5$ in.

It is believed that all these chosen variables represent reasonable practice. However, many other values could have been used, and actual experience may prove some of those chosen to be less advantageous than other values. It will be noted that the downcomer clearance above the tray has been set an

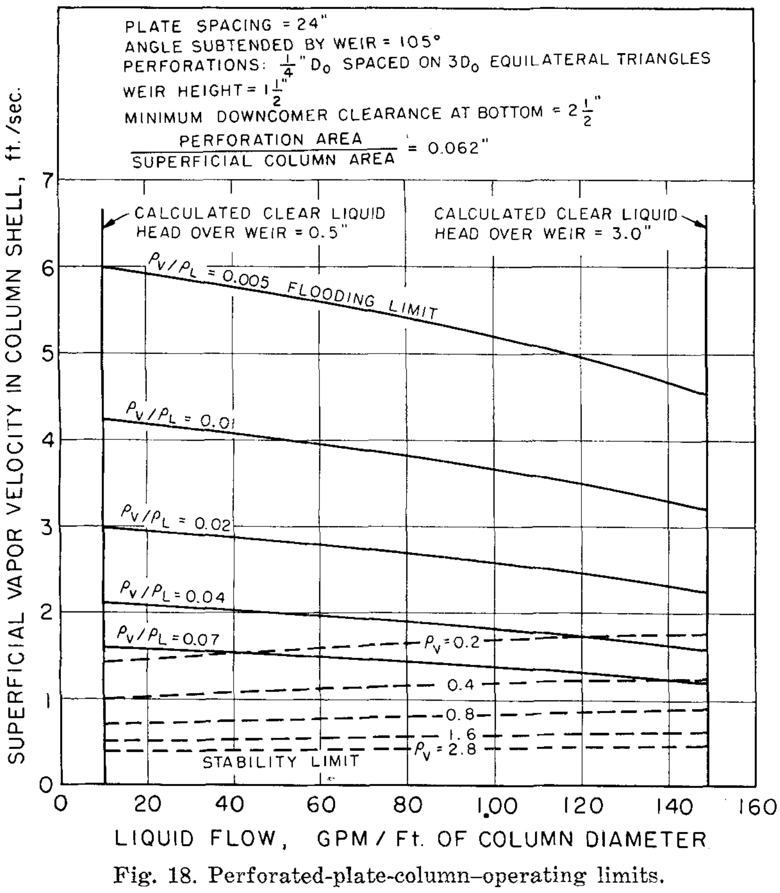

Fig. 18. Perforated-plate-column–operating limits.

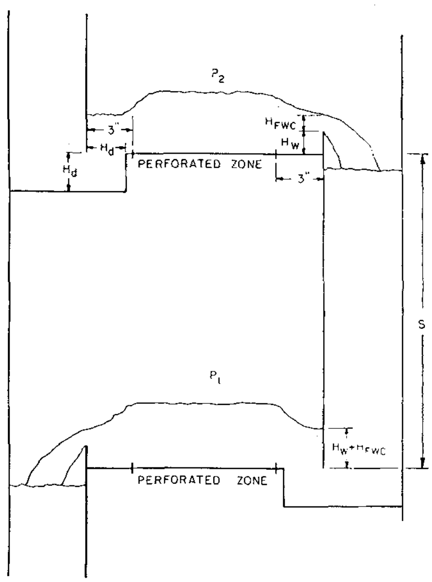

Fig. 19. Model for construction of Figure 18.

inch above the weir height, requiring the use of some sort of seal pot at the downcomer. Setting the clearance at 1.5 in. resulted in such high pressure drops at higher liquid flow rates that the vapor capacity was seriously reduced, and it appeared desirable to correct this feature. In addition to the variables above, an unperforated portion of the tray 3 in. wide was left at both downcomer and weir, in one case to leave room for the seal pot and in the other to act as a calming zone.

Figure 18 was constructed on the model shown in Figure 19. It was assumed that the hydraulic gradient across the tray was negligible, as experimentally shown by Mayfield, and that the height of partially aerated liquid at the downcomer was equal to the weir height plus the height of foam flowing over the weir, $H_W + H_{FWC}$. In addition it was assumed that the liquid in the downcomer, the liquid flowing over the weir, and the liquid just outside the downcomer were all partially aerated, i.e., still contained bubbles of vapor that had not escaped, and all had a density of 0.7 the density of clear liquid. No data are known to the authors on the density of liquid in downcomers, although unfortunately this density is of paramount importance in determining the capacity of a column. The density of 0.7 clear-liquid density assumed seemed a reasonable value from the figure of 0.4, which exists in the bubbling zone.

On the basis of Figure 19 and the assumptions made, the head balance at flooding in inches of clear liquid was taken as

$$0.7\,(S - H_{FWC}) = h_{total} + h_d$$

where S is plate spacing in inches; H_{FWC} is the height of foam flowing over the weir, in inches; h_{total} is the total head loss in the vapor flowing through the plate, inches of clear liquid; and h_d is the head loss in the liquid flowing through the constriction at the bottom of the downcomer, inches of clear liquid. Further,

$$h_{total} = 12\frac{\rho_V}{\rho_L}h_{DP} + \frac{12\Delta P_R}{\rho_L} + h_L.$$

where h_{DP} is the pressure drop for gas flow through the dry plate, ft. gas; ΔP_R is the residual pressure for flow through a wet plate, lb. force/sq.ft.; and h_L is the head of liquid in the bubbling zone. The terms h_{DP} and ΔP_R are functions of gas velocity in the perforations, which are related to superficial gas velocity through the ratio of hole area to shell area. The relationship is slightly dependent on column diameter for a constant weir angle. The ratio used in Figure 18, hole area/shell area = 0.062, is correct for a column diameter of 6 ft. and increases by only 7% up to a column diameter of 10 ft. Values of h_{DP} and ΔP_R were obtained from the relations previously given. The aeration factor of Mayfield *et al.* relating the liquid head in the bubbling zone to the calculated clear-liquid depth at the weir was used to obtain values of h_L. Values of H_{LWC} and h_{FWC} were calculated with the ordinary weir equation. The pressure drop due to liquid flow through the constriction at the bottom of the downcomer was calculated with the equation for a submerged sluice gate, correcting the velocity for the assumed density of 0.7. Entrainment also was calculated and found to be generally negligible. At the highest vapor velocity, over 6 ft./sec., for a liquid with a surface tension of 20 dynes/cm. the entrainment resulted in a calculated increase in head over the weir of about 0.1 in.

It will be noted that flooding was presumed to occur when the liquid level in the downcomer reached the top of the weir. For liquid levels above this, the weir action is changed to a submerged weir and the capacity is reduced for the same head over the weir. No particular effort was made to employ additional safety factors in the individual calculations; rather the pressure drops were calculated as accurately as possible and used without change. Because of this, and because of the high uncertainty in the density of liquid in the downcomer, a design at two thirds of the flooding limit is probably reasonable.

ACKNOWLEDGMENT

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NOTATION

A_c = area of column available for vapor flow, sq.ft.
A_o = total area of perforations, sq. ft.
D_o = diameter of perforation, in.
e_w = weight of liquid entrained/unit weight of vapor flowing
E = Murphree vapor efficiency
g_c = gravitational constant, 32.2 lb. mass (ft.)/(lb. force) (sec.^{2})
h = head loss, ft. or in. of fluid flowing
h_d = head loss from liquid flow through constriction at bottom of downcomer, in. clear liquid
h_{DP} = head loss in vapor flowing through dry plate, ft. vapor
h_L = head of liquid on tray in perforated zone, in. clear liquid
h_{total} = total head loss in vapor across tray, in. clear liquid
H_d = minimum width at bottom of downcomer for segmental downcomers, in.
H_{FWC} = height of foam flowing over weir, in.
H_{LWC} = calculated height of liquid flowing over weir based on clear-liquid flow rate in.
H_W = height of weir, in.
L = liquid flow, moles
ΔP_R = residual pressure drop, defined as total wet-plate pressure drop minus dry-plate pressure drop minus head of liquid on the tray, lb. force/sq.ft.
S = actual plate spacing, in.
S' = effective plate spacing, distance between top of foam and plate above, in.
t = plate thickness, in.
u_c = vapor velocity in column, ft./sec.
u_o = vapor velocity in perforations, ft./sec.
V = vapor flow, moles
ρ_L = liquid density, lb. mass/cu.ft.
ρ_v = vapor density, lb. mass/cu.ft.
σ = surface tension, dynes/cm.

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