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Perforated-plate performance

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Abstract—The effect of the ratio of plate thickness, T, to hole diameter, D_h, on dry-plate pressure drop has been correlated over a wide range of column size, hole area, and Reynolds number through the holes. New data are presented showing the effect of T/D_h on the wet-plate pressure-drop characteristics (for the air–water system) of perforated plates in a 15-in. diameter column having a tray spacing of 18 in. An oscillating region, where the aerated liquid mass on the tray moves back and forth perpendicularly to the direction of liquid flow, is reported. The mass flow rate of gas at which oscillation begins (the oscillation point) has been correlated with the height of clear liquid on the operating tray. In every case the oscillation point occurred well before flooding. The data presented here agree with the weepage correlation of Hughmark and O'Connell [1].

Résumé—L'effet du rapport épaisseur du plateau, T, au diamètre du trou, D_h, a été relié à la chute de pression à travers chaque plateau sec dans un champ étendu de dimension de colonne, de surface de trou, et de nombre de Reynolds à travers les trous. Pour une colonne aux plateaux mouilles (système air–eau) les nouveaux résultats presentés montrent l'effet du rapport T/D_h sur la chute de pression à travers chaque plateau. La colonne utilisée avait 15 pouces de diamètre et les plateaux perforés étaient séparés par une distance de 18 pouces. Il a été montré que dans une certaine région le liquide ventilé sur les plateaux vibrait perpendiculairement à la direction de flux. Le flux massique de gas pour lequel les oscillations commencent (le point d'oscillation) a été relié à la hauteur de clair liquide sur le plateau opérant. Dans tous les cas le point d'oscillation apparaît bien avant que le plateau soit submergé. Les résultats présentés ici sont en accord avec corrélation de Hughmark et O'Connell [1] qui permet de déterminer le flux de gas pour lequel le liquide est retenu sur les plateaux.

Zusammenfassung—Die Wirkung des Quotienten aus Plattendicke T zu Lochdurchmesser D_h wurde in Beziehung zum Druckabfall der trockenen Platte innerhalb eines weiten Bereiches der Kolonnengrösse, der Lochfläche und der Reynoldszahl in den Löchern. Für eine Kolonne von 38 cm Durchmesser mit perforierten Platten bei 46 cm Bodenabstand werden neue Werte mitgeteilt, die den Einfluss von T/D_h auf den Druckabfall der benetzten Platte beim System Luft-Wasser zeigen. Es wurde gefunden, dass in einem bestimmten Bereich die belüftete Flüssigkeitsmasse auf dem Boden senkrecht zur Strömungsrichtung ins Schwingen gerät. Der Massenstrom des Gases, bei dem die Schwingung beginnt (der Schwingungspunkt), wurde in Beziehung gesetzt zu der Flüssigkeitshöhe über dem arbeitenden Boden. In allen Fällen wurde der Schwingungspunkt vor dem Fluten erreicht. Die hier mitgeteilten Daten stimmen mit der Beziehung von Hughmark und O'Connell [1] überein, mit der sich jener Gasstrom berechnen lässt, bei dem die Flüssigkeit auf dem Boden zurückgehalten wird (weep point).

The number of technical papers appearing in the last decade or so [1-20] concerned with perforated-plate column performance is indicative of a lively interest in this type of counter-current liquid–vapour contactor. The investigations have shown that in addition to stable operation, these plates have many distinct advantages over conventional bubble-cap plates. They are easy to fabricate and are more economical than bubble-cap plates. Mayfield, Church, Green, Lee and Rasmussen [16] and Jones and Pyle [8] found that perforated-plate efficiencies were greater than those for

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bubble-cap plates under similar conditions. Kelly [13] and Zenz [20] indicated that perforated-plate columns had greater capacities than those containing bubble caps. In addition, hydraulic gradient [6, 16], entrainment [8, 12], and pressure-drop [8] characteristics for sieve plates are, in general, superior to those for bubble-cap plates.

The purpose of the work reported here was to obtain new operating data with special attention focused on the effect of the plate thickness to hole diameter ratio (T/D_h), and on the oscillating region reported by McAllister and Plank [17].

The dry–plate pressure drop using plates having various values of T/D_h was first studied extensively by Kamei *et al.* [10, 11]. Their results, and those of other investigators, indicate that for a given plate thickness, free space, and mass flow rate of air, as the hole diameter is decreased the pressure drop decreases until a value of $T/D_h \cong 2{\cdot}3$ is reached. Further decrease of the hole diameter (increase in the value of T/D_h) causes the pressure drop to increase.

It is shown in this paper that the increased dry–plate pressure drop for values of $T/D_h > 2{\cdot}3$ results from hole friction and can be calculated accurately using the usual Fanning friction factor for smooth pipes [22]. Below $T/D_h = 2{\cdot}0$ the friction term becomes negligible and the pressure drop is a function primarily of the contraction and expansion losses when the gas passes through the holes as indicated by Hunt, Hanson and Wilke [5]. All available dry-plate data (T/D_h ranging from 0·08 to 7·9) including the additional results presented here [T/D_h ranging from 0·116 to 5·333] correlate well.

Studies of pressure drop as a function of vapour rate indicate several regions displaying different types of operation. The three types of curves encountered in this work are shown in Fig. 1. The curve of Type I, Fig. 1, is that for the dry-plate runs. No liquid was flowing in the column, and the pressure drop versus flow rate curve was linear on log-log graph paper, and had a slope of approximately 2·0.

By far the most common type of curve with liquid running in the column is labelled Type III in Fig. 1. The column behaviour with this type

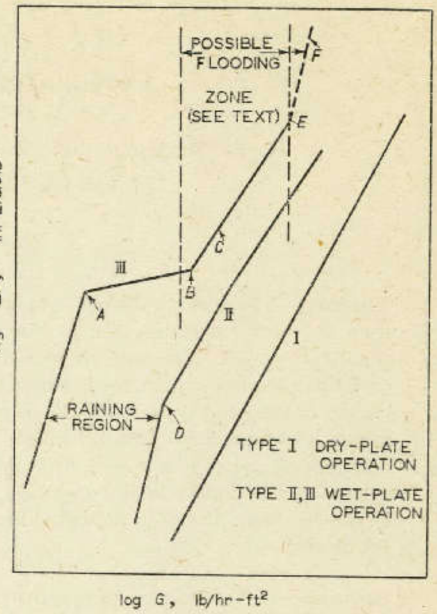

Fig. 1. Characteristic operating curves for perforated plates.

of curve is discussed in detail by Arnold, Plank and Schoenborn [2], and may be described briefly as follows. Below point *A* the liquid drains freely through the plates – the liquid "rains." Above point *A*, bubbling of gas through the liquid occurs at some of the perforations. At other perforations the liquid "weeps" through the holes. Point *B* is called the weep point. At point *B*, all the holes are bubbling, and above this point has been considered to be the normal operating region of sieve-tray columns.

The curve shown as Type II generally occurs only at low liquid rates (less than 350 lb. liquid/hr ft^2 of column) and then only with certain plates. In the work reported here only Insert IV, operating at a liquid mass flow rate of 350 lb/hr ft^2, showed a curve of Type II. Arnold *et al.* [2] reported data from a different plate (with 0·376-in. holes, 11·5 per cent free space, 0·029-in. plate thickness, 270 lb/hr ft^2 liquid flow rate) which operated in this manner. Below point *D*, Curve II, Fig. 1, liquid is draining through the perforations in the plate and no bubbling occurs. At point *D*, which might be called a weep point, the gas flow begins to support liquid on the tray and bubbling begins in some of the perforations.

The other perforations sometimes weep and sometimes bubble. At still higher gas rates, weeping appears visually to stop. However, there is no break in the performance curve. One other observation over the range of gas flow rates noted here, and by ARNOLD *et al.* [2], was that oscillation never occurred with a system having a Type II performance curve.

The oscillation behaviour in perforated-plate columns was described first by PLANK [21], and more recently by MCALLISTER and PLANK [17]. The latter showed that the effect of the oscillation increased the plate efficiency, since it decreased back-mixing on the tray. However, indications are that a detrimental effect may result due to possible flooding in the oscillating region. This latter effect is discussed more fully below. When oscillation occurs the whole liquid and frothing mass on the tray moves back and forth perpendicularly to the direction of flow of liquid. That is, if the net liquid flow is from left to right, the surging is established from front to back.

For plates and liquid flow rates having performance curves of Type III, oscillation either began at point *B*, or at a point such as *C*. In this work in general for the thick plates, over $\frac{1}{16}$in. thick, oscillation began at point *B*, while for the thin plates, 0·029in. thick, oscillation began at point *C*. For the latter plates it is significant to emphasize that no additional break in the performance curve occurred at the oscillation point. In all cases where oscillation occurred there was periodic "dumping" of the liquid through the plates on the same side of the plate as the crest of the wave. The holes on this side of the plate momentarily ceased to bubble as the wave reached its peak, and then liquid discharged through the holes as the wave began to fall.

"Flooding" in a perforated plate column can result from several causes and hence is shown as a zone of broken lines in Fig. 1. Flooding can result from (1) backing up of liquid in the downcomer, (2) expansion of the froth into the tray above, (3) splashing of the liquid into the tray above due to oscillations, (4) complete lifting of the liquid from the tray floor, (5) carry-over of all the liquid on the tray as entrainment and, (6) perhaps other possibilities. Types 1 and 2 are quite common, and result in a vertical ΔP line at the flooding velocity. Depending on the tray spacing and physical properties of the system, especially the frothing characteristics, flooding of this type might occur at any point between *A* and *E*. Type 3 is usually only a partial flooding. Once the oscillation point is reached, further increase in the gas rate at a given liquid rate only increases the violence and amplitude of the oscillations. In this study the splashing was quite often vigorous enough to carry liquid up into the tray above, even though an "average" froth height of only $\frac{1}{2}$ to $\frac{1}{3}$ of the tray spacing was observed. PLANK [21] noted action of Type 4, where all the liquid was lifted off the tray and hung as suspended drops between the plates accompanied by heavy entrainment. Whether or not this tray action can be considered to be a type of flooding is largely a matter of definition. This type of flooding is quite unstable and very easily changes to flooding of Type 5. Still further increase in the gas velocity would inevitably result in complete carry-over of the liquid in the form of entrainment (Type 5) possibly giving a curve such as *F* in Fig. 1. There may be combinations of more than one type of flooding simultaneously, or in all likelihood other mechanisms which result in flooding. In the work reported here flooding of Type 3 only was observed.

EQUIPMENT

The perforated-plate column used here was the same one used by ARNOLD *et al.* [2]. Many of the details of construction, including some photographs, are given in the above reference. A summary of some of the pertinent dimensions of the column is given in Table 1.

Table 1. *Perforated-plate column dimensions*

Number of plates	3
Inside column diameter	15 in.
Tray spacing	18 in.
Inlet weir height	$\frac{1}{2}$ in.
Outlet weir height	2 in.
Height of splash baffle (outlet side)	8 in.
Clearance between outlet weir and splash baffle	$\frac{3}{8}$ in.
Clearance under baffle, from floor of tray	$\frac{1}{2}$ in.

Table 2. Plate insert dimensions

Plate insert	*Plate thickness* T, *(in.)*	*Hole diam.* D_h (in.)	*Pitch* p (in.)	T/D_h	*Number of holes*	*Free space,** (FA) *per cent*
I	$\frac{1}{16}$	$\frac{3}{16}$	27/64	0·333	545	8·52
II	$\frac{1}{2}$	$\frac{1}{2}$	1–13/64	1·000	77	8·55
III	$\frac{1}{2}$	$\frac{1}{4}$	19/32	2·000	312	8·65
IV	$\frac{1}{2}$	$\frac{3}{16}$	27/64	2·667	545	8·52
V	$\frac{1}{2}$	3/32	14/64	5·333	2180	8·47
VI†	0·029	$\frac{1}{4}$	0·87	0·116	160	4·43
VII†	0·029	$\frac{5}{16}$	$1\frac{1}{8}$	0·093	90	3·92

*Based on column area.

†Inserts 1·4 and 1·5, respectively, used by Arnold, Plank and Schoenborn [2].

The perforated plates in this column were removable inserts for ease in changing plate thickness (T), hole diameter (D_h), and distance between holes (p). The dimensions of the inserts are given in Table 2.

All the holes were drilled or punched on a triangular pattern. It is important to note that there were no holes closer than about $1\frac{3}{8}$ in. downstream of the inlet weir, or closer than $1\frac{3}{8}$ in. upstream of the outlet weir. It was noted in this investigation, and in others [2, 14-16], that if the perforations are too close to either the inlet or the outlet weir these holes will weep continually. Also, if the holes are too close to the outlet weir, excessive froth passes under the splash baffle and over the outlet weir. Inserts I-V were made of Plexiglas, whereas Inserts VI and VII were made of stainless steel. For the Plexiglas plates, holes were drilled and the burrs were carefully removed. The stainless steel plates were punched.

Results

Dry-plate pressure drop. The dry-plate pressure drop as a function of the mass flow rate of air is shown in Fig. 2 for Inserts I-VII. The pressure loss as gas passes through a dry perforated plate results from (1) a contraction loss, (2) a friction loss in the hole, and (3) an expansion loss. Hunt, Hanson and Wilke [5] at a T/D_h ratio of 1·0 correlated their results, considering only the contraction and expansion losses. For thicker plates, $T/D_h \simeq 2{\cdot}3$, the magnitude of the friction through the holes themselves becomes important, requiring a term for the pressure loss due to friction of the Fanning type.

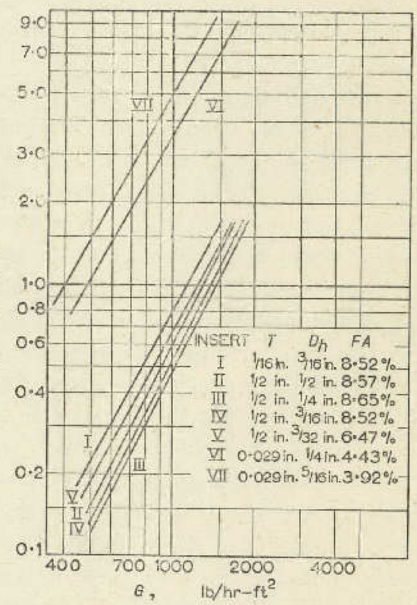

Fig. 2. Dry-plate ΔP as a function of G.

Following the approach of Hunt *et al.* sudden contraction losses in pipes [22] can be expressed as :—

$$h_c = 0{\cdot}4\left(1{\cdot}25 - \frac{A_2}{A_1}\right)\frac{V_2^2}{2g}. \quad (1)$$

For expansion,

$$h_e = \left(1 - \frac{A_2}{A_1}\right)^2 \frac{V_2^2}{2g}. \qquad (2)$$

The corresponding equation for friction losses is:-

$$h_f = \frac{4 f l V_2^2}{2g\, d_2}. \qquad (3)$$

Combining these three losses for a perforated plate, and substituting plate thickness T for l in equation (3) results in the following relation for a single plate :—

$$h = k\left[0{\cdot}4\left(1{\cdot}25 - \frac{A_h}{A_c}\right) + 4f(T/D_h) + \left(1 - \frac{A_h}{A_c}\right)^2\right]\frac{V_h^2}{2g}. \qquad (4)$$

The factor k has been added in the formulation of equation (4) since equations (1), (2) and (3) were derived for a single hole (a pipe) and not an array of parallel paths. Presumably coefficient k can take care of interference between adjacent jets, and the Couette correction and velocity-gradient irregularities within the holes. For each insert used here, h was plotted against the quantity $[0{\cdot}4\,(1{\cdot}25 - A_h/A_c) + 4f(T/D_h) + (1 - A_h/A_c)^2]\, V_h^2/2g$. In each case a straight line resulted having a slope of k. Likewise data from all other readily available sources were treated in the same manner. Fig. 3 shows the calculated k values as a function of T/D_h. The agreement of the points with the line is remarkable in view of the range of T/D_h, column diameter, free space, and hole velocity represented in Fig. 3.

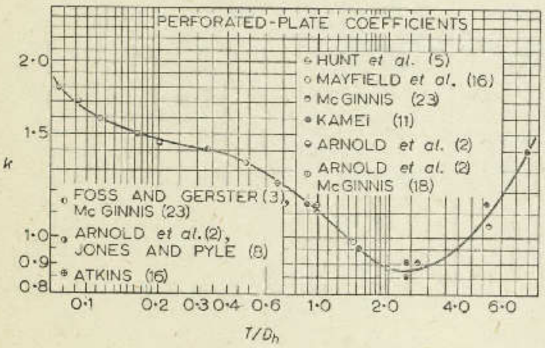

FIG. 3. Dry-plate coefficient k as a function of T/D_h.

Figure 4 shows a comparison of pressure drops calculated by the use of equation 4 and Figure 3, and experimentally determined pressure drops. The average deviation of the points from the line of equality in Fig. 4 is small.

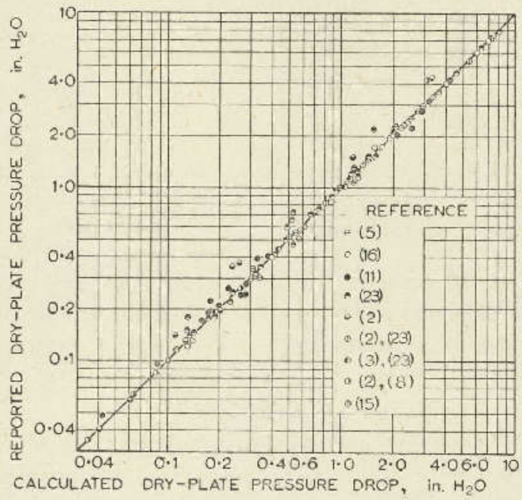

FIG. 4. Comparison of calculated and reported dry-plate pressure drop.

Wet-plate pressure drop. Figs. 5-11 show the performance curves of all the inserts used here. The wet-plate pressure drop is given for the indicated liquid rates as a function of the mass

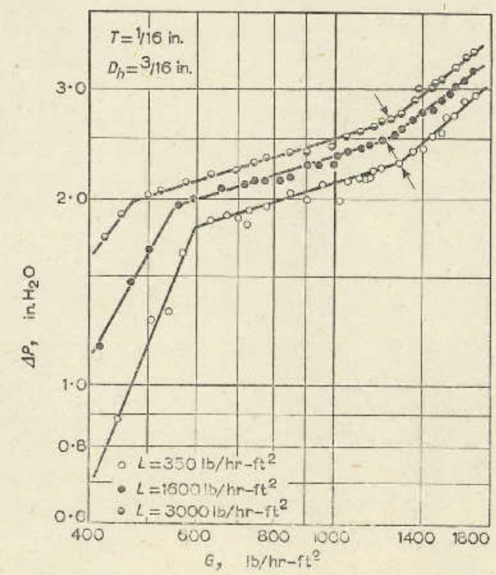

FIG. 5. ΔP as a function of G – Plate insert I.

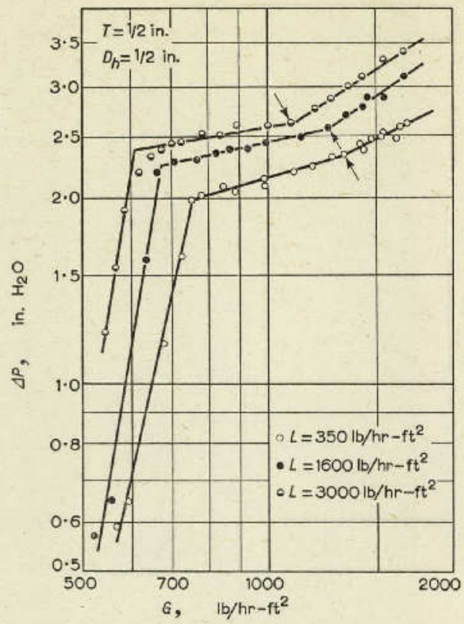

Fig. 6. ΔP as a function of G – Plate insert II.

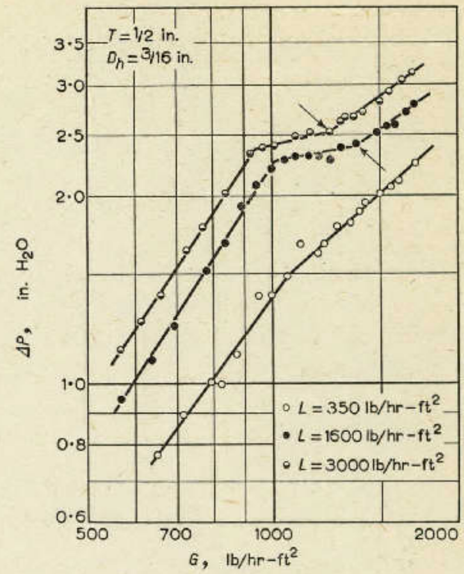

Fig. 8. ΔP as a function of G – Plate insert IV.

flow-rate of air, G, in lb air/hr ft^2 of column cross-sectional area. All of the curves are of the Type III shown in Fig. 1 with the exception that in Fig. 7 for a liquid mass flow-rate of 350 lb water/hr-ft^2. This curve is of Type II. The oscillation points are indicated in Fig. 4-10 as the small arrows.

In Fig. 12 and 13 total pressure drop minus the clear liquid head, as a function of the mass flow-rate for Inserts V and VI respectively, has been plotted. The solid line shown in these Figures is the dry-plate pressure drop. The vertical distance from the line to-the wet-plate data points is known as the " residual " pressure [5]. Fig. 14 shows the residual pressure drop as a function of T/D_h at a single mass flow-rate

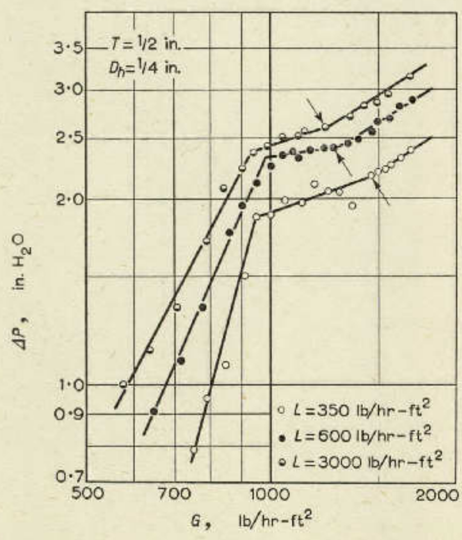

Fig. 7. ΔP as a function of G – Plate insert III.

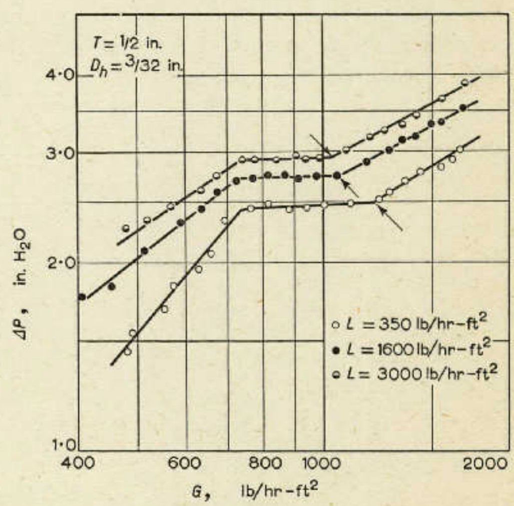

Fig. 9. ΔP as a function of G – Plate insert V.

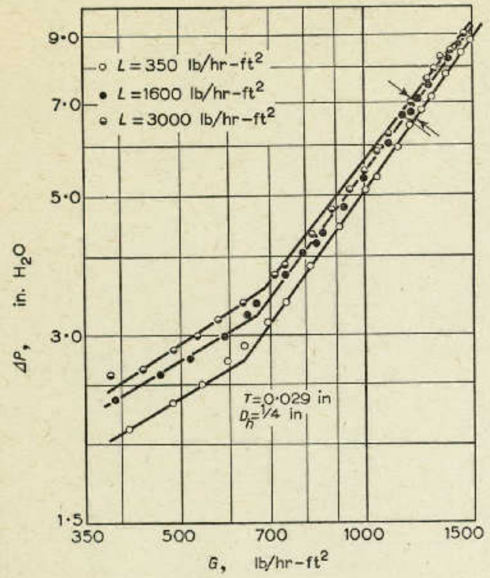

FIG. 10. ΔP as a function of G – Plate insert VI.

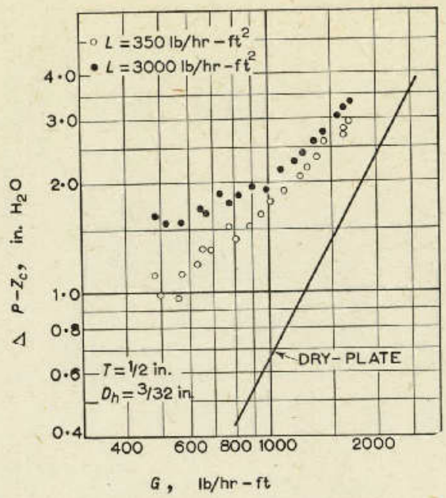

FIG. 12. Total pressure drop minus the clear liquid head as a function of G – Plate insert V.

of air. At other values of G, the residual pressure drop increases with increasing G. The data in Figs. 12, 13 and 14 show the residual pressure drop to be a function of T/D_h, L and G. An increase of L, for thick plates, results in an increase of R. Likewise R increases as T/D_h increases for constant values of L. No general correlation was made, but these data were given to indicate the general trends.

The results of this investigation and those obtained by ARNOLD *et al.* [2] show that for thin plates the residual pressure drop is affected little by changes in liquid flow-rate. The ratio of the residual pressure drop to the dry-plate pressure drop remains about constant for the thin plates. Thus the data lie above and in a line parallel to the dry-plate curve in Fig. 13. Fig. 24 of ref. [2] shows the same trend for the thin plates

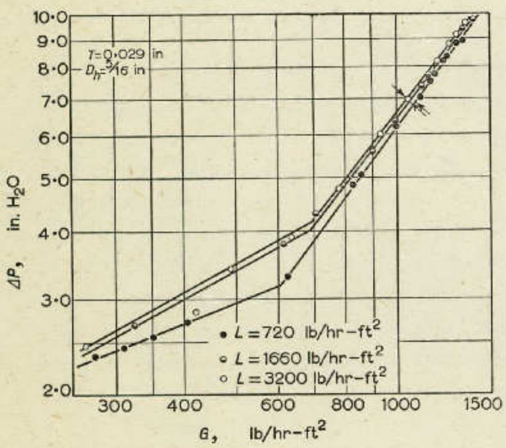

FIG. 11. ΔP as a function of G – Plate insert VII.

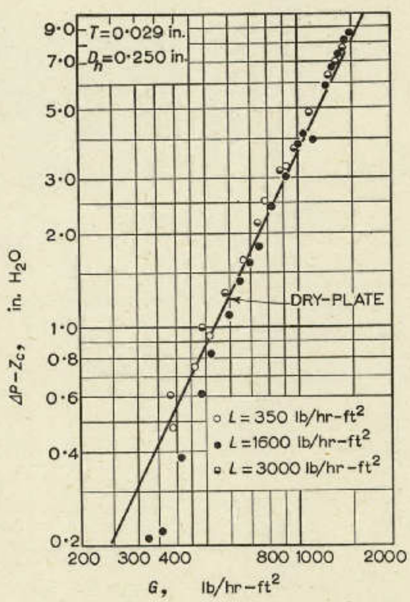

FIG. 13. Total pressure drop minus clear liquid head as a function of G – Plate insert VI.

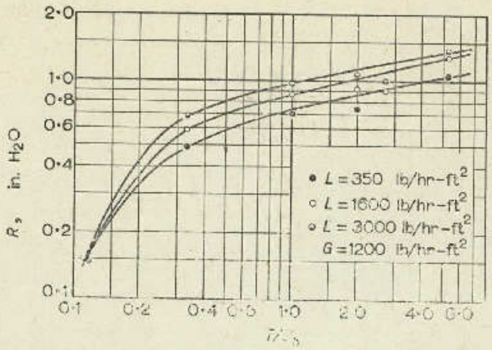

Fig. 14. Residual pressure drop as a function of T/D_h and L.

used by Arnold *et al.* [2]. For the thicker plates, however, the residual pressure drop increases with an increase of liquid flow-rate. The ratio of residual pressure drop to dry-plate pressure drop decreases with increasing gas flow-rate.

The complete set of data for Inserts I-VI giving total pressure drop, clear liquid height, froth height, gas and liquid flow-rate, etc. has been tabulated by McGinnis [23].

Weepage correlation. Fig. 15 shows the total pressure drop plotted as a function of the vapour F-factor through the holes at the weep point. The vapour F-factor is the square root of kinetic energy of the gas per unit volume. Table 3 presents the weep-point data of this investigation. The solid line in Fig. 15 is the weepage correlation proposed by Hughmark and O'Connell [1]. The data of the present investigation agree reasonably well with the correlation. However, some of the data points shown in Fig. 15 are not in the range of hole diameters included in Hughmark and O'Connell's correlation; thus the weep-points for the $\frac{1}{2}$ in. holes are out of the range of the correlation and do not agree with it. Also the data for the 3/32 in. holes ($T/D_h = 5{\cdot}33$) do not agree with the correlation. It is felt that there is a surface tension effect which should

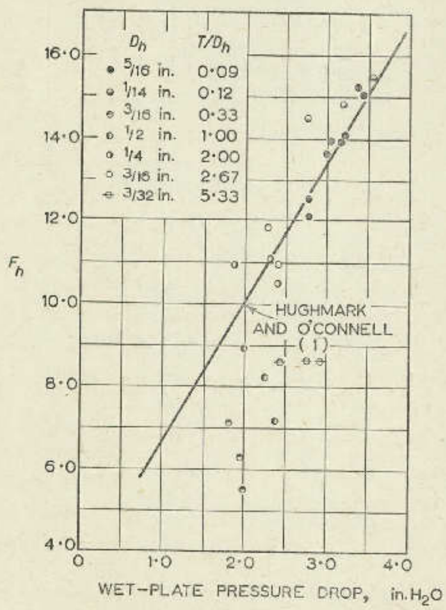

Fig. 15. Weep-point correlation.

Table 3. Weep points

Plate insert No.	L (lb H_2O/hr ft^2)	ΔP (in. H_2O)	G (lb air/hr ft^2)	F_h
I	350	1·82	610	7·07
	1600	1·96	555	6.43
	3000	2·00	470	5.45
II	350	2·00	770	8·94
	1600	2·26	710	8·23
	3000	2·37	620	7·18
III	350	1·87	940	10·88
	1600	2·32	960	11·11
	3000	2·40	910	10·54
IV	350	—	—	—
	1600	2·28	1020	11·83
	3000	2·40	945	10·96
V	350	2·44	740	8·57
	1600	2·75	740	8·57
	3000	2·92	740	8·57
VI	350	2·75	640	14·40
	1600	3·20	665	14·97
	3000	3·55	695	15·62
VII	450	3·74	645	16·4
	720	3·68	630	16·1
	960	4·06	691	17·7
	1380	3·46	586	15·0
	1660	3·86	645	16·4
	2020	4·14	688	17·5
	2450	3·46	574	14·6
	2610	3·90	649	16·5

Table 4. Oscillation points

Plate insert No.	L (lb H_2O/hr ft^2)	G (lb air/hr ft^2)	ΔP (in. H_2O)	Z_c (in. H_2O)
I	350	1220	2·22	0·68
	1600	1160	2·42	0·91
	3000	1150	2·60	1·00
II	350	1330	2·33	0·60
	1600	1260	2·56	0·78
	3000	1100	2·65	1·06
III	350	1470	2·18	0·34
	1600	1280	2·43	0·72
	3000	1220	2·61	0·92
IV	1600	1375	2·40	0·51
	3000	1240	2·53	0·79
V	350	1200	2·50	0·46
	1600	1050	2·76	0·82
	3000	1030	2·95	0·98
VI	350	1238	6·81	0·83
	1600	1187	6·74	0·91
	3000	1306	7·95	0·95
VII	450	1223	7·99	0·57
	720	1220	7·64	0·83
	960	1211	7·87	0·91
	1380	1200	7·83	0·87
	1660	1191	7·13	0·71
	2020	1182	7·40	1·14
	2450	1170	8·00	0·95
	2610	1166	8·03	1·06
	3200	1148	7·51	1·30

be included in the correlation, and that this effect may be magnified by the high T/D_h ratio.

Oscillation-point correlation. Table 4 presents the oscillation point data of this investigation, and Fig. 16 presents the air mass flow-rate as a function of the clear liquid height, both at the oscillation point. The agreement is quite satisfactory except for Insert V ($\frac{1}{2}$ in. thick, 3/32 in. holes). It should be noticed that the weep-point correlation for this particular insert was also unsatisfactory. Possibly some surface tension effect incorporated into both correlations would improve the agreement of the data for Insert V with that of the other inserts. It is interesting to note that the oscillation-point correlation was based on the column mass flow-rate whereas the weepage correlation required the hole velocity to bring the data into the proper order.

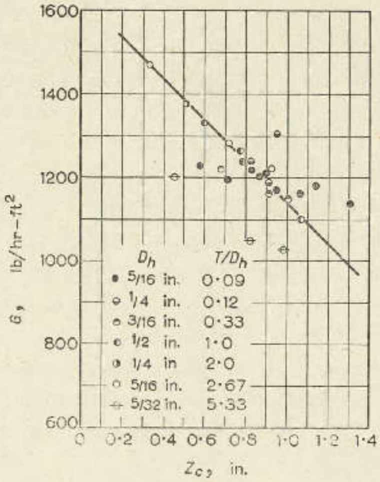

FIG. 16. Oscillation-point correlation.

The clear liquid height, Z_c, at the centre of the operating tray was used in the oscillation-point correlation, and was measured with a manometer. One leg of the manometer was inserted through the plate from beneath and was made flush with the top surface of the plate. The other leg of the manometer was mounted in the vapour space above the plate. The manometer reading itself was considered to be the clear liquid height, measured in inches or centimetres of liquid. It represents the hydraulic pressure of the liquid and froth on the plate in terms of clear liquid head. The clear liquid height, along with the froth height has been shown by PLANK [24] to be an important quantity in characterizing aeration on the tray. Aeration in turn is one of the factors which affects mass-transfer efficiency in liquid–phase controlling systems [24].

The clear liquid height is a difficult quantity to measure accurately. It fluctuates constantly, especially in the oscillation region described above, and is often less than 1 in. in magnitude, even with a 2-in. weir. The clear liquid height and the froth height undoubtedly hold many of the keys to a complete understanding of tray hydraulics, as well as mass-transfer efficiency on perforated-plate trays, bubble-cap trays, and the like.

Conclusions

(1) The dry-plate pressure drop for perforated plates is described well by equation (4) and Fig. 3.

(2) At constant hole diameter and free area, dry-plate pressure drop decreases with increasing plate thickness (i.e. T/D_h increases) until hole friction becomes appreciable (at $T/D_h \cong 2 \cdot 3$); then a reversal of this trend occurs.

(3) Four distinct types of plate action were encountered in this study – raining, weeping, stable operation, and oscillation.

(4) Periodic liquid and froth surges or oscillations can occur at high gas rates and is accompanied by periodic liquid dumping through the perforations near the column walls.

(5) For thin plates, residual pressure drop is shown not to be a function of the liquid flow-rate, it increases with increasing gas flow-rate, but the ratio of residual pressure drop to dry-plate pressure drop is essentially constant. For thick plates the residual pressure drop is a function of T/D_h, G and L.

(6) The results of the investigation are in agreement with the weepage correlation of Hughmark and O'Connell [1].

(7) The mass flow-rate, G, lb air/hr ft^2 of column area, at which oscillation begins is shown to be a linear function of the clear liquid height at the oscillation point.

Notation

A_1 = cross-sectional area of the larger pipe, ft^2
A_2 = cross-sectional area of the smaller pipe, ft^2.
A_c = column cross-sectional area, ft^2.
A_h = total perforation area, ft^2.
D_h = diameter of the perforations, in.
D_2 = diameter of the smaller pipe, ft.
ΔP = pressure drop across a plate, in. of fluid.
f = Fanning friction factor for smooth pipes, ref. [20]
FA = total perforation area-to-column area ratio, per cent.
F_h = F-factor through the holes, $V_h \sqrt{\rho_g}$, where ρ_g = gas density, lb/ft^3.
g = acceleration of gravity, ft/sec^2.
G = mass flow-rate of gas, lb gas/hr ft^2 of total column cross-sectional area.
h = head loss across a dry perforated plate, ft of gas flowing.
h_c = head or pressure loss due to contraction, ft of fluid.
h_e = head or pressure loss due to expansion, ft of fluid.
h_f = head or pressure loss due to friction, ft of fluid
k = a dimensionless coefficient.
l = length of pipe, ft.
L = mass flow rate of liquid, lb liquid/hr ft^2 of total column cross-sectional area.
p = pitch, the centre-to-centre distance between the perforations, in.
R = residual pressure loss (total pressure loss minus dry plate loss minus Z_c).
T = plate thickness, in.
V_2 = average velocity in the smaller pipe, ft/sec.
V_h = average velocity in a perforation, ft/sec.
Z_c = clear liquid height, in.

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