Gas Absorption in a Fin-Wall Conduit

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Gas absorption and pressure drop were studied in a fin-wall conduit; a fin-wall conduit is a rectangular duct with fins placed on two internal walls perpendicular to the axis of flow. Pressure drop data were obtained with the air-water system. Gas absorption data were obtained with the air-ammonia-water system, and were corrected for the expected liquid-phase resistance by the use of oxygen desorption data. The pressure drop per transfer unit is on the order of 0.05 in. of water per transfer unit.

Gas-liquid contacting devices that accommodate a wide range of liquid and gas rates at a low pressure drop, and that handle particulate-bearing gases have wide application. The purpose of this paper is to present mass transfer and pressure drop characteristics of one such device: the fin-wall conduit.

The fin-wall conduit is a rectangular duct with transverse fins attached to one or more internal walls; it is shown in Figure 1. Three attractive qualities of this device prompted its study: the vortex flow patterns between the fins, the open construction, and the reproducibility of its critical dimensions.

Figure 2, which was obtained in a water tunnel with the aid of lycopodium powder, shows typical single-phase flow patterns between fins; flow is from left to right. In turbulent flow, the formation and the form of these vortex patterns depend only on the ratio of fin spacing to fin height. Visual studies indicate that there is a rapid exchange of material between the mainstream and the vortices. The rotational velocity of a vortex, by visual observation, increases with increasing mainstream velocity.

A small part of the volume of a fin-wall conduit, 2 to 5%, is occupied by fins; the other 95 to 98% is open. This suggests that the fin-wall conduit may be capable of handling large volumes of gas, which will make it useful in the wet scrubbing of gases that contain particles.

The fin-wall conduit has few important dimensions; these are the fin spacing, the fin height, and the distance between fin walls. By comparison, the important dimensions of a packed column are not uniform and cannot be explicitly specified. It is postulated that the ease of specifying and measuring the dimensions of the fin-wall conduit will allow controlled design for desired characteristics.

Desorption of oxygen from water and absorption of ammonia into water were studied. Oxygen desorption is generally considered to be a case in which all of the resistance to transfer is contained in the liquid phase. Ammonia absorption into water was, at one time, assumed to be a case in which all of the resistance to transfer was contained in the gas phase; this is not now regarded as completely true. The oxygen-water equilibrium data of reference *4* and the ammonia-water equilibrium data of reference *7* were used.

The equipment utilized in this study consisted of four experimental conduits, designated as columns A, B, C, and D. The columns were rectangular conduits formed by two fin walls (aluminum) and two smooth walls (transparent plastic). The spacing between adjacent fins of the same fin wall is designated as S; the height of a fin as H; the minimum distance between fins of opposite fin walls as b; the width of the conduit along the fin wall as W. The minimum cross-sectional area for flow is A, or bW. The maximum cross-sectional area for flow is A + 2HW. Table 1 lists some dimensions of the conduits.

The conduit that was being studied was situated on top of the air-inlet box that was a 1-ft. cube. Air was introduced at the side of the box; it ascended through the fin-wall conduit, out the top, to the exhaust system. Water was introduced near the top of the conduit through small holes in a 3/8-in. copper tube designed to distribute the water evenly over the two fin walls (*10*). The water descended through the conduit into the air-inlet box from which it was withdrawn.

PRESSURE DROP

For flow in a circular pipe

$$\frac{\Delta P}{X} = \frac{2\rho f U^2}{g_c D} \tag{1}$$

In noncircular conduits, experience has led to the equivalent diameter concept. The equivalent diameter for use in Equation (1) is defined as

$$D_{eq} = \frac{4\ (\text{cross-sectional area of conduit})}{(\text{wetted perimeter of conduit})} \tag{2}$$

Thus in flow between infinite parallel plates the equivalent diameter is twice the plate spacing.

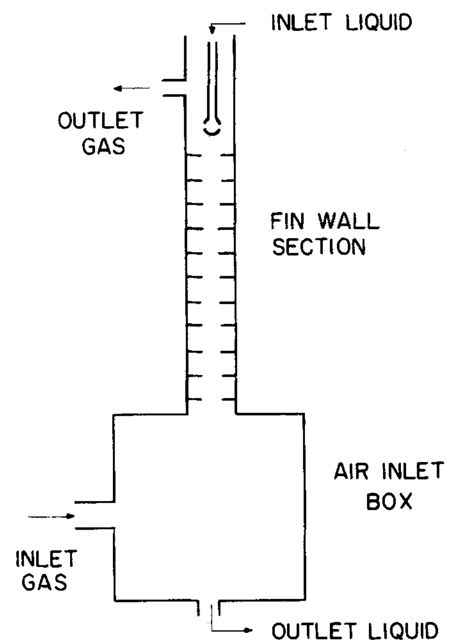

Fig. 1. Fin-wall conduit.

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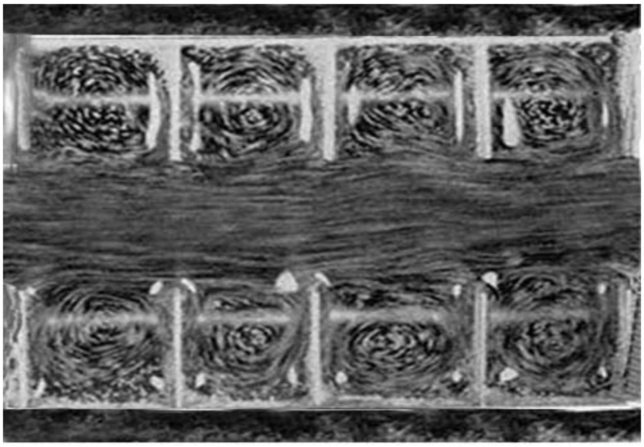

Fig. 2. Flow patterns between fins. Fin spacing = fin height.

In a fin-wall conduit with two fin walls, the equivalent diameter at the minimum cross-sectional area is

$$D_{eq} = \frac{4Wb}{2(W + b)} \quad (3)$$

The use of the equivalent diameter calculated at the minimum cross-sectional area is convenient in this work; it has been used in work on fin tubes (*2, 6*).

Equation (3) contains the term $(W + b)$, which is related to the sum of the drag on the fin walls and the drag on the smooth walls. If we neglect the drag due to the smooth walls, thereby replacing the term $(W + b)$ with the term (W), Equation (3) becomes

$$D_{eq} = 2b \quad (4)$$

There exist some pressure drop data for fin-wall conduits made of only one fin wall and three smooth walls (*1, 3*). If we neglect the drag of the smooth walls as compared to that of the fin wall, the equivalent diameter becomes

$$D_{eq} = 4h \quad (5)$$

The minimum distance between the fins and the opposite smooth wall is h.

For a conduit with two fin walls, Equations (1) and (4) yield

$$\frac{b\Delta P}{X} = \frac{\rho f U^2}{g_c} \quad (6)$$

For a conduit with one fin wall, Equations (1) and (5) yield

$$\frac{2h\Delta P}{X} = \frac{\rho f U^2}{g_c} \quad (7)$$

The pressure drop characteristics of each experimental column were determined; the pressure drop over the entire column was obtained at various gas and liquid rates. Figure 3 shows the results for column A; the data from other columns are similar. The ordinate is the logarithm of pressure drop per unit length in inches of water per foot. The abscissa is the logarithm of the air rate in pounds per hour per square foot based on the minimum cross-sectional area. The parameter is water rate in pounds per hour per square foot of minimum cross-sectional area. The data for a dry column can be represented by a single straight line; the data for an irrigated column can be represented by two intersecting straight lines. The point of intersection of the two straight lines herein is designated the loading point.

The pressure drop characteristics of the experimental columns resemble those of a packed column. In an irrigated packed column, however, three intersecting straight lines are usually required to represent the data. The slope of the line below the loading point is about the same in each case, that is 1.8 to 2.0. The pressure drop in wet drained packing is higher than the pressure drop in dry packing; this difference is not present in the fin-wall conduit.

TABLE 1. COLUMN DIMENSIONS

	Column A	Column B	Column C	Column D
Fin-wall length, ft.	3.22	3.22	3.25	3.25
b, ft.	0.0495	0.0938	0.0495	0.0495
S, ft.	0.0379	0.0379	0.0807	0.0807
H, ft.	0.0388	0.0388	0.0402	0.0812
S/H	0.976	0.976	2.01	0.994
A, sq. ft.	0.0251	0.0476	0.0251	0.0251
A', sq. ft.	0.0646	0.871	0.0660	0.108

Note: For each column the width, W_o is 0.508 ft. The fin thickness is 0.00267 ft.

In Figure 4 the pressure drop per unit length in inches of water per foot in the experimental columns is compared with the pressure drop per unit length in columns packed with Raschig rings (*12*). The abscissa is the air rate based on the maximum cross-sectional area; the use of the maximum area is necessary for a direct comparison. The figure shows that the pressure drop for a fin-wall conduit is lower than that for Raschig rings.

The effect of liquid rate on pressure drop is shown for 1-in. and 1½-in. ceramic Raschig rings (*9*) in Figure 5. The data for fin-wall conduits, based on the maximum cross-sectional area for flow, are also shown. The ordinate A_L is the ratio of the pressure drop of an irrigated column to the pressure drop of a dry column, both at the same gas rate. The abscissa is liquid rate based on maximum cross-sectional area. The use of the maximum cross-sectional area is necessary for direct comparison; if the data for columns A, B, C, and D are plotted on a graph using the minimum cross-sectional area, three distinct curves are obtained; the data of columns A and B fall on the same curve. Figure 5 is valid for any gas rate below loading.

Calvert and Hodous (*3*) report pressure drop data for rectangular conduits with one fin wall. If we assume that all the momentum transfer is to the fin wall, we may use Equation (7). Figure 6 is a plot of $\frac{b\Delta P}{X}$ vs. air rate on

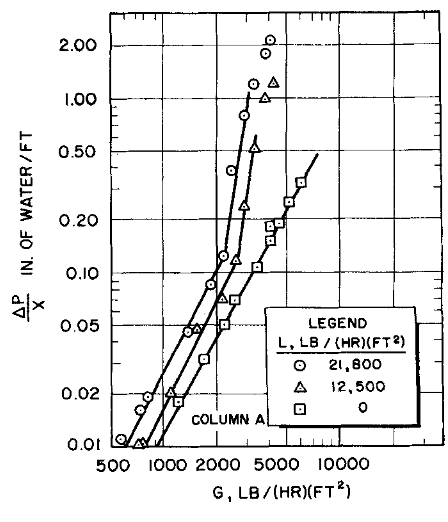

Fig. 3. Pressure drop vs. gas rate. Column A: air-water.

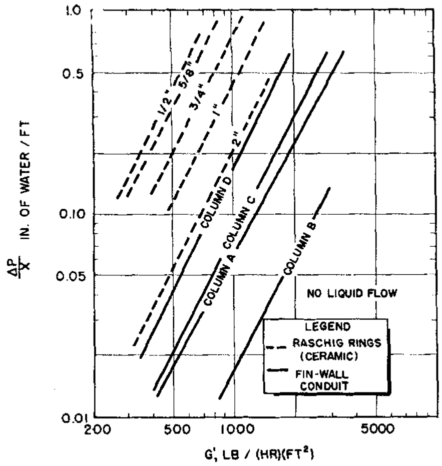

Fig. 4. Pressure drop vs. gas rate.

logarithmic coordinates for columns A, B, and D; it is also a plot of $\frac{2h\Delta P}{X}$ vs. air rate for the data of Calvert and Hodous. The data points are not shown. The fin height is approximately equal to the fin spacing. The lines for columns A, B, and D almost coincide; the lines for Calvert and Hodous's columns are definitely separate, with the line for the smallest minimum distance between the fin wall and the opposite smooth wall being the highest. The line for the largest spacing is lowest and is in the range of those for columns A, B, and D. In column C, the fin spacing is approximately twice the fin height; the line for column C, which is not shown in Figure 6, would be higher than the lines of columns A, B, and D.

The comparison shown in Figure 6 is not completely valid. A correction should be made to the data of single fin-wall conduits to account for the drag of the smooth walls. The correction would lower the three curves for the data of Calvert and Hodous by approximately 15%, which would enhance the correlation. The purpose of the graph, however, is to show that a close approximation of the pressure drop in a single fin-wall conduit can be obtained by merely neglecting the effect of the smooth wall.

The friction factor defined by Equation (6) for columns A, B, and D is approximately 0.07 at a Reynolds number, based on equivalent diameter, of 10,000; that of column C is approximately 0.09. Braun and Knudsen (*2*) presented plots of friction factor vs. the ratio of fin spacing to fin height for fin tubes. These plots show single maxima at ratios of from 4 to 5½. Column C has a ratio of 2, whereas the other columns have ratios of 1. Thus the higher friction factor for column C is in qualitative agreement with the results of Braun and Knudsen.

The friction factors, from Equation (7), calculated from the data of Calvert and Hodous (*3*) and those calculated from the data of Boelter et al. (*1*) also lie in the range

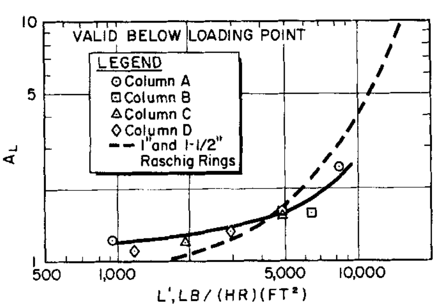

Fig. 5. Effect of liquid rate on pressure drop. A_L vs. liquid rate.

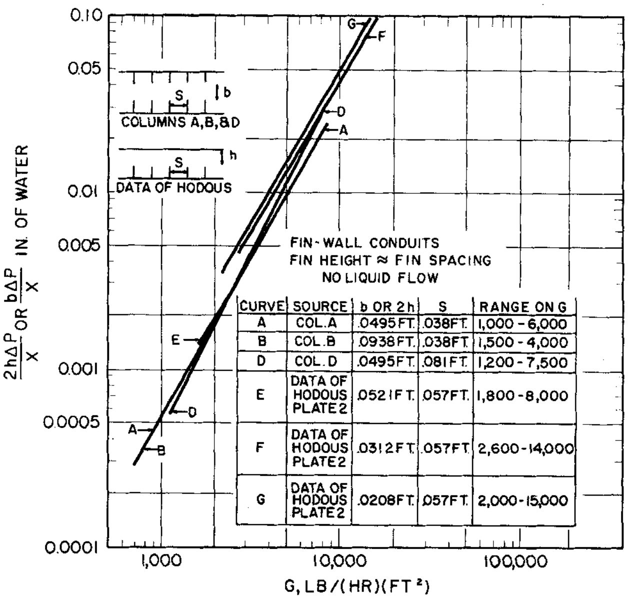

Fig. 6. $\frac{b\Delta P}{X}$ or $\frac{2h\Delta P}{X}$ vs. gas rate.

0.05 to 0.10. Friction factor plots are given in reference *10*. Additional work is necessary before a complete friction factor chart for fin-wall conduits can be prepared.

The gas and liquid rates at loading were determined from the pressure drop curves for each column; the data are well represented by

$$G = 4590 \left[\frac{L}{G}\right]^{-0.301} \tag{8}$$

OXYGEN DESORPTION

Figure 7 is a plot of the total number of liquid-phase transfer units for column A vs. the liquid rate in pounds per hour per square foot based on the minimum cross section for flow. The data have been corrected to 25°C. and have also been corrected for end effects; the end-effect correction is approximately 25% of the observed number of transfer units. The data for columns B, C, and D are similar and are given in Table 2.* Below the loaded region, liquid rate has little effect; with increasing gas rate the number of transfer units increases. In the loaded region the number of transfer units increases with increasing liquid rate and increasing gas rate.

AMMONIA ABSORPTION

The mass transfer process can be described in terms of a penetration theory model (*10*). Necessary assumptions are that the dominant transport mechanism in the gas phase is that between the rotating vortex and the wetted fin wall, and that the peripheral velocity of a captured vortex is about 1/3 the velocity of the gas through the column (*8*). Also, transfer between the vortex and the main stream of the gas is assumed to be very rapid, so that the composition of the captured vortex would be the same as that in the adjacent portion of the main stream. The resulting equation for the height of a gas-phase transfer unit is

$$H_G = \frac{0.767Sb\sqrt{G}}{\sqrt{D'\rho(S+2H)}} \tag{9}$$

* Tabular material has been deposited as document 8404 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or 35-mm. microfilm.

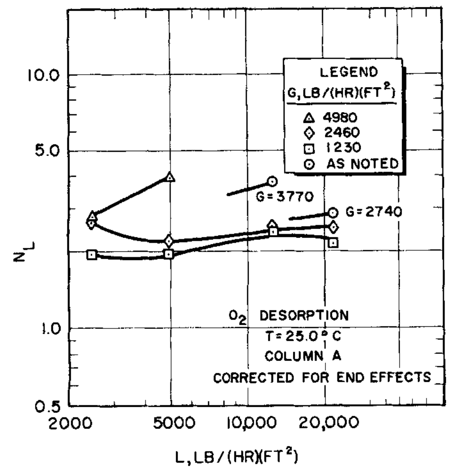

Fig. 7. Number of transfer units vs. liquid rate.

Substituting values for the air-ammonia system

$$H_G = \frac{3.0Sb\sqrt{G}}{\sqrt{S + 2H}} \tag{10}$$

If H_G is plotted against $Sb\sqrt{\dfrac{G}{S + 2H}}$, a straight line through the origin of slope 3.0 should be obtained.

The results for column A are shown in Figure 8; the results for all columns are given in Table 3.* Below the loaded region, the number of overall gas-phase transfer units decreases with increasing gas rate and increases with increasing liquid rate. Above the loading point, the number of transfer units increases with increasing gas rate and with increasing liquid rate. The data have been corrected for end effects; the end-effort correction is approximately 20% of the observed number of transfer units.

Figure 9 shows the results for columns A and B as a plot of H_Ga vs. gas rate. In this plot, the data have been corrected for end effects and for the expected liquid-phase resistance by use of the oxygen desorption data. The data for columns A and B, below the loaded region, are brought together by this plot. The agreement is very good; where the only variable is the spacing between fin walls, interpolation by this type of correlation is recommended. The surface of interface per unit volume, a, is calculated by dividing the fin-wall area by the free volume.

$$a = \frac{2\,(S + 2H)}{Sb} \tag{11}$$

The prediction of Equation (10) is tested in Figure 10. Equation (10) predicts a straight line relationship between H_G and $Sb\sqrt{\dfrac{G}{S + 2H}}$ for columns where the fin spacing is approximately equal to the fin height. In similar graphs for columns A and D, the data can be represented by straight lines through the origin below the loading point. In a graph for column C, in which the fin spacing does not equal the fin height, the straight line relationship does not apply as well as in the graphs for columns A, B, and D.

Equation (10) predicts a slope of 3.0; the lines through the data points have slopes that are different from 3.0. The actual curves approach Equation (10) as the liquid rate increases. This disagreement of the data with Equation (10) arises, at least in part, from the assumption that the liquid-phase resistance in the ammonia-water system may be estimated using data obtained with the oxygen-water system.

From available data (9), one would expect that the height of a transfer unit obtained from corrected ammonia-water data would be three to four times larger than that obtained from other gas-phase controlling data. The agreement between ammonia-water data and gas-

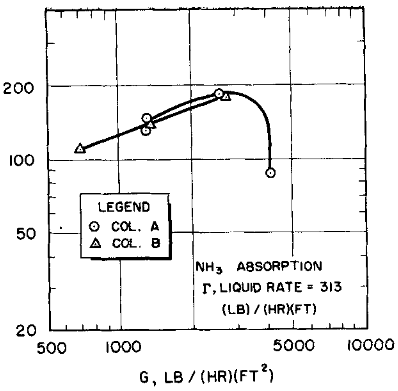

Fig. 9. H_Ga vs. gas rate.

* See footnote on page 787.

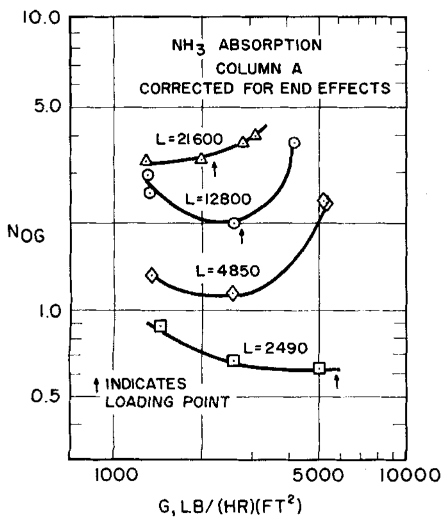

Fig. 8. Number of transfer units vs. gas rate.

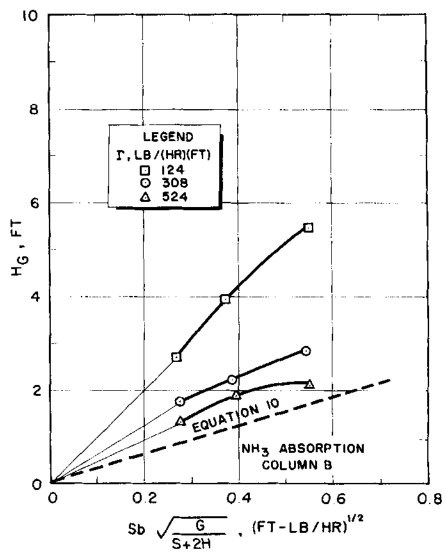

Fig. 10. H_G vs. $Sb\sqrt{\dfrac{S}{(S+2H)}}$

TABLE 5. AMMONIA-WATER DATA

$$H_{OG} = \frac{\alpha G^{\beta}}{\Gamma^{\gamma}}$$

Column	α	β	γ	Range on G	Range on
A	6.49	0.291	0.644	1,280 lb./(hr.)(sq. ft.) to loading point	61.5 to 536 lb./(hr.)(ft.)
B	2.66	0.442	0.573	680 lb./(hr.)(sq. ft.) to loading point	123 to 530 lb./(hr.)(ft.)
C	3.05	0.200	0.817	1,330 lb./(hr.)(sq. ft.) to loading point	129 to 540 lb./(hr.)(ft.)
D	2.88	0.523	0.836	1,280 lb./(hr.)(sq. ft.) to loading point	122 to 511 lb./(hr.)(ft.)

phase controlling data should improve as liquid rate is increased. In Figure 10, the height of a transfer unit observed for the ammonia-water system is several times larger than the predicted values for a gas-phase system; the agreement improves as the liquid rate is increased.

Ammonia absorption in column A is compared with ammonia absorption in 2-in. Raschig rings (*11*) in Table 4.* The pressure drop per transfer unit is 0.09 to 0.15 in. of water for 2-in. Raschig rings and 0.03 to 0.05 in. of water for column A. The height of a transfer unit is greater in the fin-wall conduit but the pressure drop per transfer unit is lower. Similar tables could be presented for other packings and other columns; the conclusions would be the same.

The ammonia-water data are summarized in Table 5 where empirical equations are presented.

CONCLUSIONS

An investigation of pressure drop and gas absorption in a fin-wall conduit has been described.

The pressure drop data, obtained with the air-water system, are presented as head loss per unit length. The pressure drop characteristics are similar to those of a packed column; the fin-wall conduit, however, has a much lower pressure drop per unit length than does the usual packed column. An accurate estimate of pressure drop and loading point in a fin-wall conduit can be made with the obtained data.

A postulated model for gas-phase controlled gas absorption indicates that the height of a transfer unit will increase with the square root of gas rate. The model will predict heights of gas-phase transfer units that are in reasonable agreement with the data if the fact that the ammonia-water system is not completely gas-phase controlled is recognized.

In the absence of the additional data required to present generalized results for design purposes, the equations of Table 5 are recommended.

ACKNOWLEDGMENT

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NOTATION

a = surface of interface per unit volume, sq.ft./cu.ft.
A = minimum cross-sectional area for flow, sq.ft.
A' = maximum cross-sectional area for flow, sq.ft.
A_L = ratio of pressure drop in an irrigated column to pressure drop in a dry column, both at the same gas rate
b = minimum spacing between opposite fin walls in conduit containing two fin walls, ft.
D = diameter, ft.
D_{eq} = equivalent diameter, ft.
D' = diffusivity, sq.ft./hr.
f = friction factor
g_c = a conversion factor, 32.17 $(lb._m)(ft.)/(lb._f)(sec.^2)$
G = gas rate based on minimum cross-sectional area, lb./(hr.)(sq.ft.)
G' = gas rate based on maximum cross-sectional area, lb./(hr.)(sq.ft.)
h = minimum spacing between fin wall and opposite plate in conduit with one fin wall, ft.
H = fin height, ft.
H_G = height of a gas-phase transfer unit, ft. (corrected for end effects)
H_{OG} = height of an overall gas-phase transfer unit, ft. (corrected for end effects)
L = liquid rate based on minimum cross-sectional area, lb./(hr.)(sq. ft.)
N_{OG} = number of overall gas-phase transfer units (corrected for end effects)
N_L = number of liquid-phase transfer units at 25°C. (corrected for end effects)
P = pressure, in. of water
S = fin spacing, ft.
U = average velocity through minimum cross-sectional area for flow, ft./sec.
W = width of conduit, ft.
X = length of column, ft.

Greek Letters

α see Table 5
β see Table 5
γ see Table 5
Γ = liquid flow rate, lb./(hr.)(ft.)
ρ = density

* See footnote on page 787.

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