A Study of Entrainment, Perforated Plate Column—Air-Water System

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A correlation has been developed interrelating entrainment as a function of plate spacing, weir height, hole size, liquid rate, and gas rate with a section of a 30-in. diameter column and the air-water system. The correlation is empirical, but approximately 90% of the over 900 points of data fall within ± 25% of the correlation. Hole diameters of 1/16 to 1/4 in., weir heights from 0 to 2 in., plate spacing from 12 to 24 in., gas rates from 770 to 1,700 lb./hr./sq. ft., and liquid rates from 2,800 to 12,000 lb./hr./ft. of weir length were studied as variable. Entrainment was found to increase with gas rate, decrease with weir height, increase with hole size, decrease with plate spacing, and could increase or decrease because of interaction effects as the liquid rate increases.

In any vapor-liquid contacting device used for the purpose of attaining an approach to equilibrium between the phases, entrainment of some of the liquid phase in the vapor may seriously affect the efficiency of the process. In plate absorption and distillation columns excessive liquid in vapor entrainment can reduce efficiency as much as 25% in sections of the column, particularly where the concentrations in the vapor and liquid are widely different. From another standpoint, where pure distillate products are required and specifications permit only traces of impurities, only slight amounts of entrainment may cause off-test products.

Entrainment from bubble-cap trays has been studied by a number of investigators (*2, 4, 6, 8, 10*) and many others, and correlations for estimating the quantity of entrainment have been presented.

Entrainment from perforated plates has been evaluated experimentally by a number of investigators. Jones and Pyle (*8*) found that entrainment from perforated plates amounts to approximately 20% of that from bubble-cap plates over the normal operating range. In addition the entrainment curves were very different, with the slope of the entrainment curve vs. vapor flow rate much greater than that of the bubble cap at high F factors. Hunt, Hanson, and Wilke (*7*) studied entrainment in a 6-in. diameter column with a nonliquid flow system. They found that entrainment was independent of hole velocity and dependent on column velocity and plate spacing. They correlated entrainment with column velocity and a plate spacing factor based upon the estimated distance from the surface of the bubbling liquid to the plate above. They found the entrainment ratio to be inversely proportional to the 3.2 power of the plate spacing factor.

While these investigations developed information relative to the qualitative relations of entrainment with the factors considered, all of the variables possibly affecting entrainment had not been included. Therefore this investigation was initiated to evaluate the effect of plate spacing, weir height, hole size, liquid rate, and gas rate on entrainment with a section of a 30-in. diameter column and the air-water system.

EQUIPMENT

The column used in this study was a 6 in. wide rectangular section of a 28-¾ in. perforated plate distillation column (Figure 1). The ends, flanges, and sides were made from R-grade Plexiglas. The column consisted of two sections with the test plate flanged between them. The downcomer in the upper section was rectangular, 1½ in. by 6 in., and the inlet weir height was 2 in. The upper section was 32 in. in height and the cross-sectional area was 1.12 sq. ft. The lower section of the column, 18 in. in height, contained a downcomer, 2 by 6 in. in cross section.

The test plate consisted of two sections, the perforated plate section and a support section, which was underneath the perforated section. The support formed the bottom of the seal on the inlet downcomer and the calming sections. Four different perforated plates were tested in this investigation, and their pertinent characteristics are listed in Table 1. All of the plates were made from perforated 302 stainless steel sheets with the perforation pitch and hole diameter so arranged to give a 10% free hole area based on the perforated plate. The free area of the holes was 7.29% based on the free column area. The perforated plates were fastened to the support plate by the flange bolts and weirs. The weirs were made of ¼ in. thick aluminum plate and were spaced so that the outside edges of the inlet and outlet weirs were 24 in. apart.

Manometer taps were placed in the flange ¼ in. above the edge of the plate to give an indication of the effective height of the clear liquid on the plate. The tops of the manometers were attached to the column 12 in. above the plate so that only the pressure differential caused by the liquid on the plate was indicated. The pressure drop through the plate was measured by a 30-in. U tube inclined water fluid manometer.

The entrainment collector tray was made from 26-gauge galvanized sheet metal. The tray consisted of seven V troughs oriented parallel to the liquid flow path and were so arranged to give two 180-deg. direction changes to the air as it passed through (Figure 2). The tray was covered with a 2-in. layer of mist eliminator mesh made of type 304 stainless steel. The entrained water was carried from the V troughs by a mainfold made from copper tubing. A piece of plastic tubing conducted the water from the end of the column to either a 1,000-ml. buret or a 100-ml. buret which was used to measure the quantity of entrainment, over definite periods of time.

Air was furnished to the column by three 1-hp. industrial type of vacuum cleaner electric blowers. Because the minimum amount of air required was greater than the output of one blower, one blower was allowed to run at constant speed throughout the tests. This was arranged so that its output was conducted through straight conduit into the lower section of the column. The other two blowers were mounted on either side of the manifold system which was connected to the column with a 6-in. section of 2-in. pipe. The output of the blower system was controlled by regulating the speed of the two side-mounted blowers with a variable auto transformer. The air flow was measured by determining the pressure drop across 2⅜ in. of the 6-in. section with a calibrated, single-leg, inclined manometer containing water.

A recirculation water system was used wherein the water was pumped from the reservoir through the column by a pump

TABLE 1. PLATE CHARACTERISTICS

Hole diameter in.	Hole spacing, in.	Plate thickness, USS gauge
1/4	3/4	18
3/16	9/16	18
1/8	3/8	18
1/16	3/16	20

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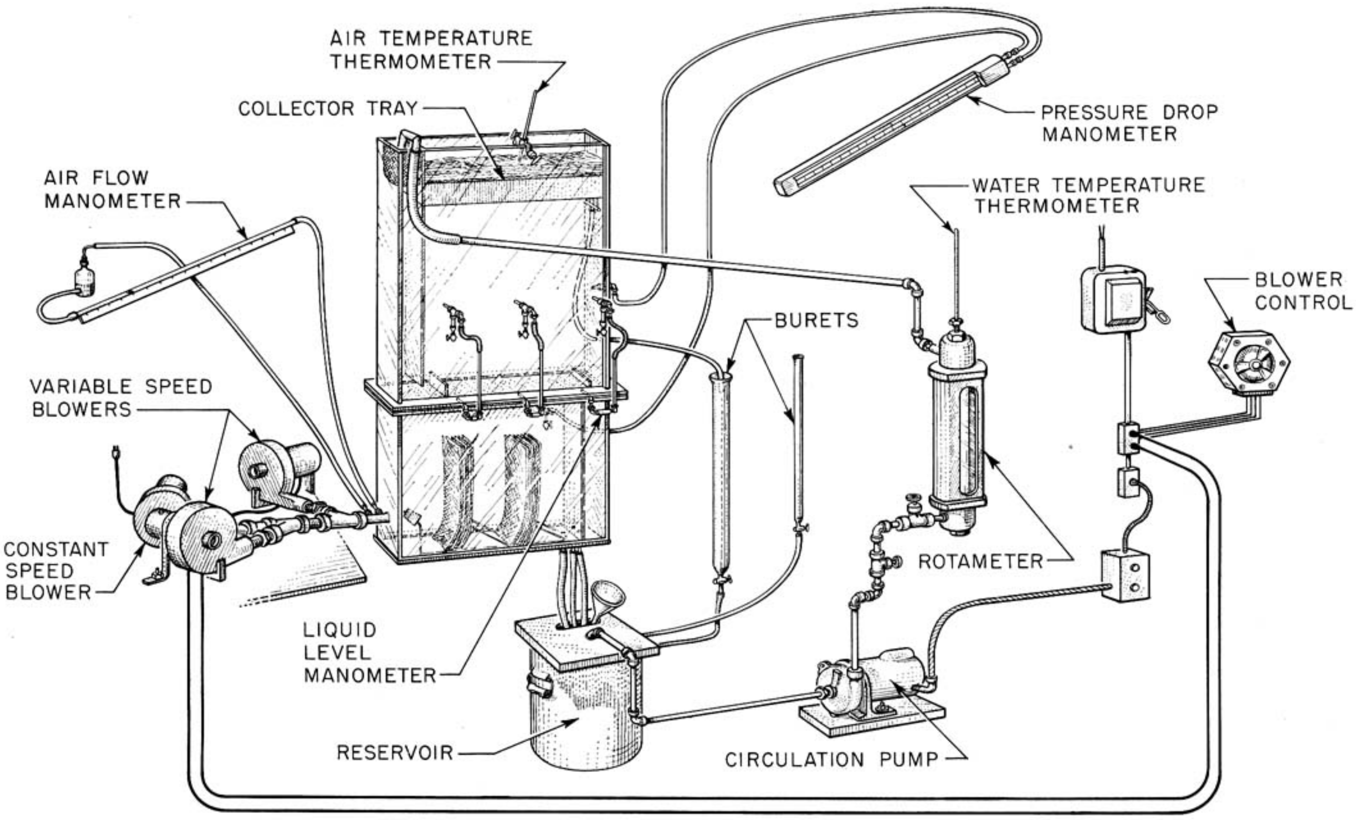

Fig. 1. Perforated-plate column and accessories.

having a capacity of 10 gal./min. at a 50-ft. head. The water rate was measured with a flow rater. All piping and fittings were either brass or copper with the exception of a 2-ft. piece of rubber tubing that served as a flexible connection to the column. The water was removed from the lower section to the reservoir by gravity feed.

EXPERIMENTAL PROCEDURE

The rotameter in the water line was calibrated by weighing the amount of water effluent for a fixed period of time at several flow rates. The orifice in the air line was calibrated by determining the velocity of air in the column at a number of different flow rates throughout the range of the air flow. Because there was a very low pressure drop between the blowers and the atmosphere, the effect of absolute pressure on the orifice was neglected.

A single run consisted of measuring the entrainment at five different air rates and one liquid rate for a given weir height, hole size, and plate spacing. Plate spacing was taken as the distance between the perforated plate and the bottom of the collector tray. A series of runs was started by fixing the water rate at the lowest rate used (2,800 lb./hr.-ft. of weir) and the air rate at the highest rate used (1,680 lb./hr.-sq. ft.). Approximately 4 min. was allowed for the entrainment collector tray to reach equilibrium. The entrainment was measured for a period of 2 min., and then the air was lowered to the next lower rate and the process repeated until five air rates had been used. For each tray the highest weir and lowest plate spacing were used first. After five runs at each plate spacing and weir height were made, the plate spacings were increased. When three plate spacings were completed, the weir height was lowered. After all combinations

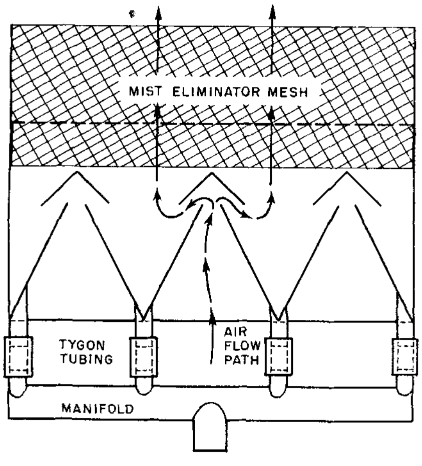

Fig. 2. Collector tray.

TABLE 2. RANGE OF VARIABLES

Variable	Range
Liquid rate	2,800 to 11,900 lb./hr.-ft. of weir
Gas rate	772 to 1,680 lb./hr.-sq. ft.
Hole size	1/16, 1/8, 3/16, and 1/4 in.
Weir height	0, 1/2, 1, and 2 in.
Plate spacing	12, 18, and 24 in.

TABLE 3. EQUIVALENT VAPOR RATES AT 60°F. AND 14.7 LB./SQ. IN. ABS.

G, lb./hr.-sq. ft.	u_c, ft./sec.	u_h, ft./sec.	F_c	F_h
1,680	6.11	83.8	1.68	23.2
1,523	5.54	76.0	1.53	21.0
1.350	4.91	67.4	1.36	18.6
1,140	4.15	56.9	1.15	15.7
772	2.80	28.4	0.77	10.6

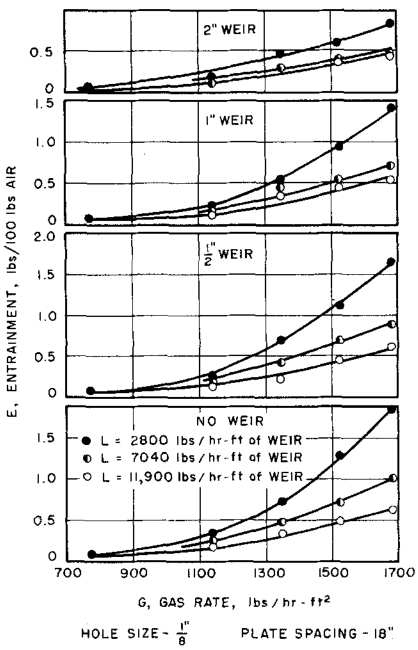

Fig. 3. Entrainment as a function of gas and liquid rate and weir height.

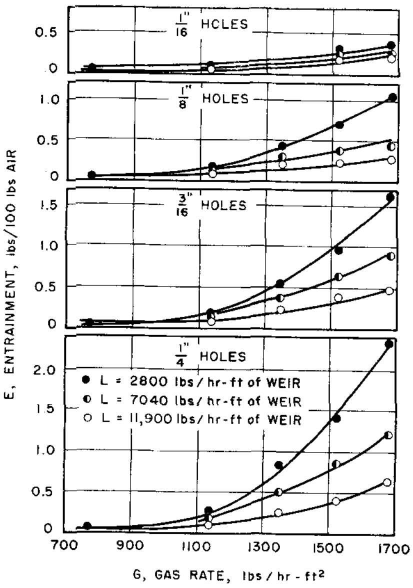

Fig. 4. Entrainment as a function of gas and liquid rate and hole diameter.

of plate spacing and weir height were completed for each tray, the tray was changed. Table 2 lists the range of variables covered in this investigation.

EXPERIMENTAL RESULTS

In this investigation the total hole area was held constant so the hole velocity was independent of the hole size for a given mass flow rate. (Calculations indicated variation in air humidity within the range observed during the experiments had little or no effect on entrainment.) Table 3 lists the vapor rates of this investigation in various units.

Figures 3, 4, and 5 show the effect of the gas rate on the entrainment. In every case the entrainment increased with an increase in the gas rate. Baker

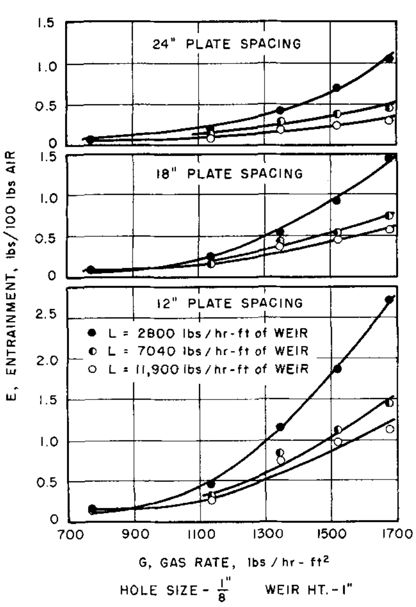

Fig. 5 Entrainment as a function of gas and liquid rate and plate spacing.

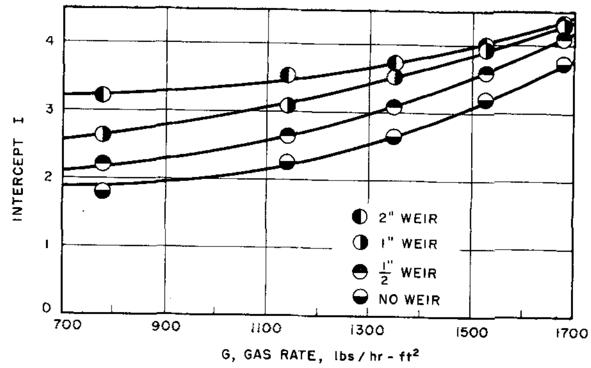

Fig. 6. Intercept as a function of gas rate and weir height.

and Holbrook (3) found that doubling the mass velocity in a bubble-cap column resulted in a tenfold increase in entrainment. The results of this investigation indicate increases in entrainment roughly six to twelve times as the result of doubling vapor mass flow rate. Figures 3, 4, and 5 also show the effect of the liquid rate on the entrainment. The effect of the liquid rate on the entrainment is dependent on the gas rate. At the gas rate of 772 lb./hr.-sq. ft. the entrainment increased with an increase in the liquid rate. This effect was most noticeable with the smaller hole sizes, that is, 1/16 and 1/8 in. At the higher gas rates, that is 1,350 lb./hr.-sq. ft. and above, the entrainment decreased with an increase in the liquid rate. This is direct disagreement with Kamei, Takamatsu, and Umeshita (9) who said "the volume of overflow and the height of weir did not influence (to) the driving force of entrainment directly."

Figure 3 shows the effect of weir height on entrainment. The entrainment decreases as the weir height increases. Eduljee (5) stated that for bubble caps the entrainment is directly proportional to the static seal. The static seal with bubble caps is comparable to the weir height with perforated plates. It should be noted however that a majority of the work done by Eduljee was at vapor rates below the minimum rate that was used in this investigation, so that it is possible that at low air rates the effect will be reversed.

Figure 4 shows the effect of hole size on the entrainment. The entrainment increased with an increase in hole size. This is in agreement with Arnold et al. (1) who suggested that the entrainment increased somewhat with an increase in hole size.

Figure 5 shows the effect of the plate spacing on entrainment. The entrainment decreases with an increase in the plate spacing. As this is in agreement with all of the investigators, it apparently is independent of the tray type. Reducing the plate spacing from 24 to 12 in. increases the quantity of entrainment in the range of from three to six times.

Hunt et al. (7) have presented a generalized correlation for entrainment. Their studies were made in a 6-in. column with a static liquid system which was arranged so that a constant liquid head could be maintained on the plate. This arrangement eliminated the effect of the liquid rate and also the direct effect of the weir height from their correlation. They presented the following equation:

$$E = 0.22\left(\frac{73}{\sigma}\right)\left(\frac{u_c}{S'}\right)^{3.2} \quad (1)$$

In order to use this correlation effectively the actual bed height must be known so that the effective plate spacing may be determined. In the present investigation the bed height was measured as well as the entrainment. It must be noted however that because of sloshing and frothing the bed height measurements were accurate only to possibly 0.5 in. A number of measurements were made and averaged to arrive at the final values. The data obtained indicated that the bed height was a linear function of the liquid rate and that the effect of the hole size was negligible. It was found that the bed height in inches can be represented by the following equation:

$$B = \frac{(0.094 + 0.014\,h_w^2)L}{1000} + I \quad (2)$$

where I is given by Equation (3) through (6) depending on the weir height.

No weir:

$$I = 3.2 - \frac{3.23G}{1{,}000} + 2.13\,(G/1000)^2 \quad (3)$$

½-in. weir:

$$I = 2.22 - \frac{1.16G}{1{,}000} + 1.35\,(G/1000)^2 \quad (4)$$

1-in. weir:

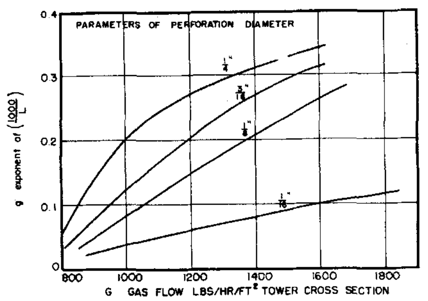

Fig. 7. Exponent of (1,000/L) as a function of *D, G*.

$$I = 2.22 - \frac{0.029G}{1{,}000} + 0.74\ (G/1000)^2 \tag{5}$$

2-in. weir:

$$I = 3.57 - \frac{1.23G}{1{,}000} + 0.996\ (G/1000)^2 \tag{6}$$

Equation (2) represents the data in this investigation with an average deviation of bed height less than ¼ in. Equations (3), (4), (5), and (6) are plotted in Figure 6.

With Equation (2) used to determine the effective spacing an attempt was made to find correlations relating the effect of the variables to the constants in Equation (1). Each constant was found to be a function of the liquid rate, weir height, hole size, and plate spacing, but it was not possible to resolve them into simple functions of the independent variables. It should be said however that for a given plate spacing, weir height, hole size, and liquid rate an equation in the form of Equation (2) will accurately describe the effect of the gas rate. In the calculations involving Equation (2) the surface tension of the water was assumed to be 73 dynes/cm., and the surface tension correction term $73/\sigma$ was neglected.

CONCLUSIONS

The entrainment increases with an increase in hole size, decreases with an increase in the plate spacing, increases with an increase in the gas rate, decreases with an increase in the weir height at gas rates above 1,000 lb./hr.-sq. ft., and decreases with an increase in the liquid rate when the gas rate is above 1,000 lb./hr.-sq. ft.

CORRELATION

Mathematical evaluation of over 900 points of entrainment data was carried out on the IBM-650 computer.

Two types of correlation were attempted. In the first case entrainment was correlated by the relation

$$\ln E = K \ln[(D/S)(1/L)^g (G)^f] + B \tag{7}$$

K and B are constants for each hole diameter.

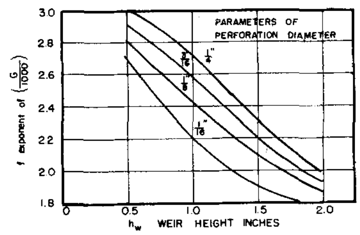

Fig. 8. Exponent of (G/1,000) as a function of *D* and h_w.

The functions are shown in Figures 7 and 8 and the entrainment correlation in Figure 9. Approximately 90% of the 900 points of data fall within ± 25% of the correlation.

The second type of correlation attempted was that based on dimensional analysis. The dimensionless groupings included the properties of viscosity density and surface tension of the phases, as well as the flow rates and dimensions. The relation was found to be

$$E\frac{\rho_A}{\rho_W} = a\left(\frac{L}{\mu_w}\right)^b \left(\frac{GD}{\mu_w}\right)^c \left(\frac{h_w}{D}\right)^d \left(\frac{S}{D}\right)^e \left(\frac{\sigma D \rho_A}{\mu_A \mu_W}\right)^f \left(\frac{\rho_W \mu_A}{\rho_A \mu_W}\right)^g \tag{8}$$

The average deviation of the calculated from the experimental values was ± 25%. The form of the correlation equation is very complex and unwieldy, and the constants were of such an order of magnitude that this was considered highly unsatisfactory.

A simplified equation of the following form

$$E\left(\frac{\rho_A}{\rho_W}\right) = a\left(\frac{H}{S}\right)^b \left(\frac{LD}{\mu_W}\right)^c \left(\frac{\sigma}{\mu_W V_A}\right)^d \tag{9}$$

was studied, but the correlation did not give as good agreement with the observed data as that of Equation (7).

NOTATION

- B = height of the expanded bed on the plate, in.
- D = hole or perforation diameter, in.
- E = entrainment, lb. water/100 lb. air
- F = F factor, (vapor velocity) (vapor density)$^{0.5}$ units of feet, second, pounds
- F_c = F factor based on superficial column velocity
- F_h = F factor based on hole velocity
- f = function of weir height and hole diameter
- G = gas rate, lb./hr.-sq. ft. of tower cross section
- g = function of hole size and gas flow rate
- h_L = equivalent height of clear liquid on the plate, in.
- h_W = height of the weir, in.
- L = liquid rate, lb./hr.-ft of weir length
- ρ = density, lb./cu. ft.
- S = plate spacing, in.
- S' = effective plate spacing (S-B), in.
- u_c = superficial column velocity, ft./sec.
- u_h = hole velocity, ft./sec.
- surface tension, dynes/cm.
- μ_W = viscosity of water
- μ_A = viscosity of air

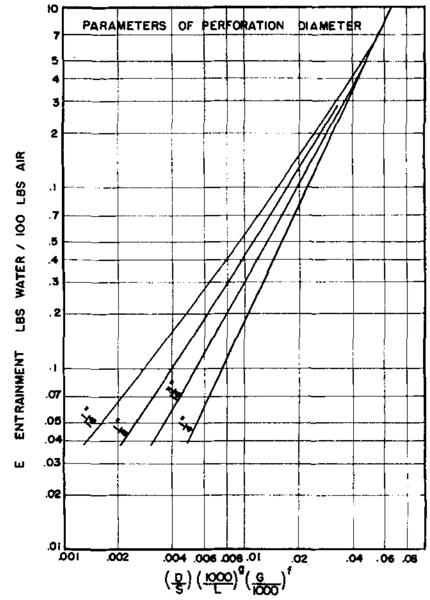

Fig. 9. Entrainment correlation.

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