Entrainment from Bubble-cap Trays

P. T. ATTERIDG, E. J. LEMIEUX, W. C. SCHREINER, and R. A. SUNDBACK

The M. W. Kellogg Company, New York, New York

Data on liquid entrainment are reported for rectangular-cap bubble trays on 24-in. tray spacing for an air-water system. Several tray variations were studied, and entrainment is given for trays containing eight, twelve, and sixteen caps a tray. Some hydraulic characteristics (pressure drop, liquid backup, minimum vapor velocity, and downflow froth height) are also reported. It was found in this study that decreasing liquid path length increased the entrainment from a bubble-cap tray and increasing tray bubbling area decreased entrainment. It was also found that decreasing slot area generally had no effect on liquid entrainment over the range investigated.

In recent years the design of fractionation towers has become highly competitive. Designers are faced with the problems of designing trays with higher vapor and liquid loadings than ever before. In both the petroleum and the chemical industries better fractionation is required to produce purer chemicals, as well as better grades of petroleum products. In order to obtain better fractionation with more heavily loaded bubble-cap trays, various chemical and petroleum engineering companies have instigated development programs to study bubble-cap tower hydraulics, as well as the various factors which affect fractionation. A tower development program was begun several years ago by The M. W. Kellogg Company to study the hydraulics of its rectangular-bubble-cap trays, including the factors which affect the entrainment of liquid between trays.

Some of the data obtained in the more recent development program on rectangular-bubble-cap trays were previously reported in a paper by Houghland and Schreiner (*5*). This paper dealt exclusively with bubble-tray hydraulics and contained data that were obtained on 18-in. tray spacing with one- and two-tray operation. Since these were published, an additional bubble-cap tray was added to the experimental tower and tray performance was studied at other tray spacings.

This paper presents the information taken with trays which had eight, twelve, and sixteen rectangular bubble caps a tray and which were spaced 24 in. apart. These trays were 18 in. wide by 63 in. long and were equivalent to the center section of a 7-ft.-diam. commercial bubble-cap tower. The first section of the paper gives the hydraulic characteristics of these trays and supplements the previous paper by Houghland and Schreiner (*5*). The second section presents entrainment data.

The amount of entrainment data available in the literature is fairly limited, being for the most part reported for fairly small experimental towers with round-cap bubble trays under a limited range of vapor and liquid rates. In the past 10 or 15 years very few additional entrainment data have been published, although entrainment has become more and more important as a factor in good tower and tray design. Furthermore, no data have ever been published for rectangular- or tunnel-cap trays of the type used in this study. The studies that were concluded on a commercial-size section of a 7-ft.-diam. tray were made to determine the effects of tray and cap modifications on liquid entrainment, as well as on tray hydraulics. The present paper, although limited to one tray spacing, 24 in., shows the effects on entrainment of bubbling area, length of liquid path, and slot area. Owing to the size of the trays used, it was also possible to study entrainment, as well as the hydraulics of rectangular trays under a wide range of vapor and liquid loadings.

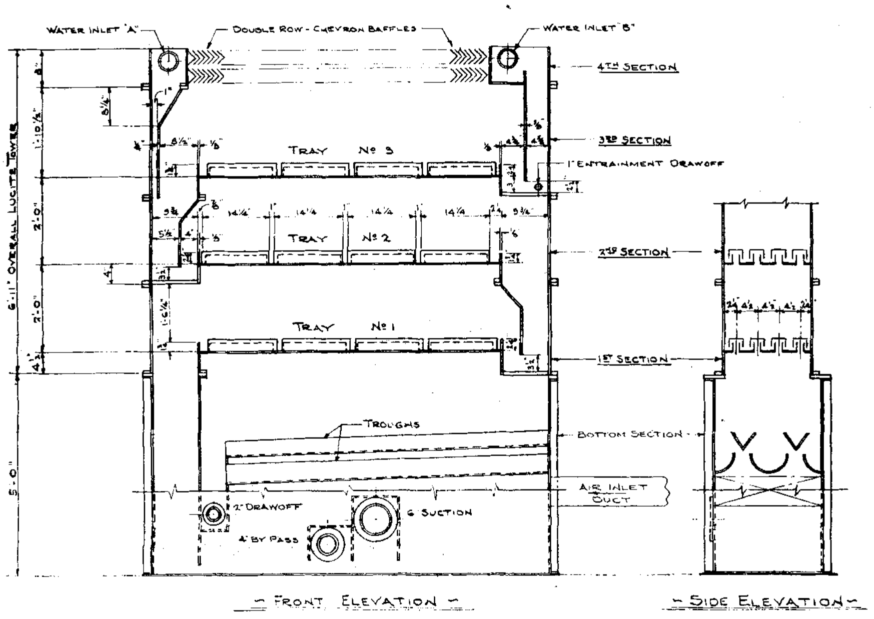

Fig. 1. Experimental-tower drawing.

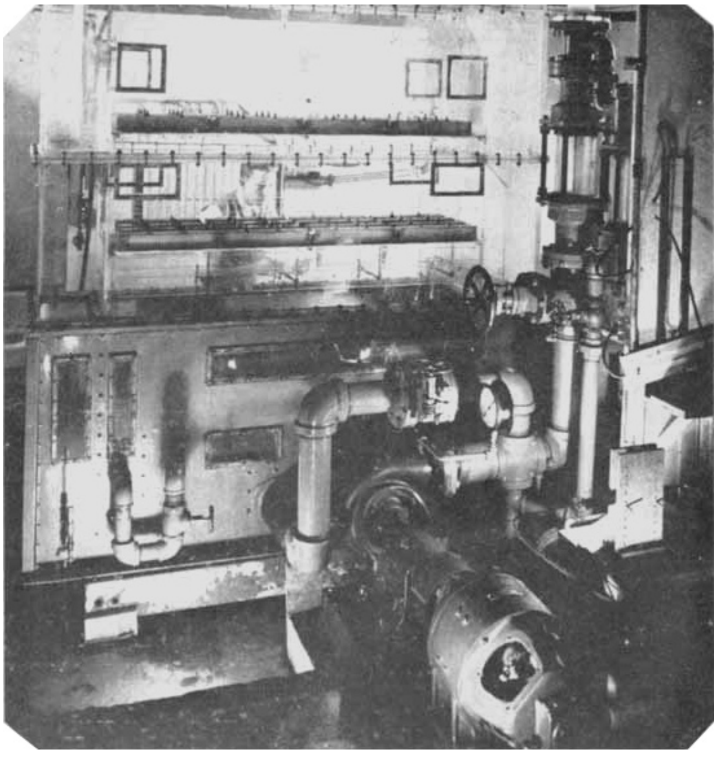

Fig. 2. Experimental tower.

Entrainment data based on various means of measurement on several types of trays have been reported in the literature. Strang (*12*), Sherwood and Jenny (*10*), Volante (*14*), Pyott, Jackson, and Huntington (*8*), and Chillas and Weir (*2*) measured entrainment from bubble-cap trays using an air-water system. Ashraf, Cubbage, and Huntington (*1*) reported experimental work on three differently sized gas absorbers. Holbrook and Baker (*4*) obtained entrainment data using a steam-salt water system. Peavy and Baker (*7*), using an ethanol-water system, measured entrainment colorimetrically. Thomson (*13*) also used an ethanol-water system, and Rhodes and Slachman (*9*) used a benzene-toluene system. Souders and Brown (*11*) pointed out in their paper that entrainment in fractionating columns affects plate efficiency and limits the maximum vapor velocity that gives satisfactory operation.

EXPERIMENTAL COLUMN

The experimental column consisted of a 6 ft. 10¾ in. by 1 ft. 6 in. rectangular box-like shell. That portion of the shell which held the trays was made of Lucite plastic to permit visual observation of all phases of tray operation. This construction was strong and could be disassembled easily to provide for the necessary changes in tray layout. The size of the shell was chosen to provide a tray which had a length of path which could be compared directly to a commercial-size tower. The tower shell consisted of flanged sections which could be removed so that the number of trays, as well as the tray spacing, could be varied fairly easily. In this study the tower contained five sections: a bottom section which contained a collection tank for the recirculation of water and semicircular troughs which could be used to collect liquid dumping from the risers; a top section which contained a double row of angle baffles to minimize splashing from the top of the tower; and three tray sections, each of which contained an 18- by 63-in. bubble-cap tray. Figure 1 gives the front elevation of the experimental tower. Figure 2 is a photograph which shows two tray sections of the tower and the water-pumping equipment. Water was pumped from the collection tank to the top of the tower by a centrifugal pump. Calibrated rotameters measured the water flow to the unit. Water could be pumped to either the middle or the top tray, depending on the type of operation that was desired. Air was blown to the bottom of the tower below the first tray section through either of two ducts by means of a 6,000 cu. ft./min. centrifugal blower powered by a 60-hp., 440-volt electric motor. Two interchangeable ducts were used: one 12¼ in. in diameter, the other 5¾ in. In either case the air flow was measured by a calibrated Pitot tube at the center of the duct. The smaller duct was calibrated at four rates and the larger at three. Paired traverses agreed within 1%. The plot of duct flow (by traverse) with the specific station reading showed a fit to linearity of within 1%. The manometer reading was good to 0.01 in.

Suitable lines were provided for collecting entrainment to the top tray. Entrainment rate was determined by drawing off liquid from the dry upper tray during the entrainment runs. Pressures at various sections of the tower were measured with vertical or inclined manometers. All temperatures were measured with ordinary Fahrenheit thermometers.

The trays were constructed of No. 12 U.S. Standard gauge, 12% Cr, type-410 stainless steel and consisted of 1¼ by 13⅜ in. No. 14 U.S. Standard gauge risers that were fitted with 2¾ by 14¼ in. No. 16 U.S. Standard gauge rectangular bubble caps. Details of the bubble-cap trays and the rectangular bubble caps used in this study are given in Figures 3 and 4, respectively.

EXPERIMENTAL PROCEDURE

Three types of tower operation were used in the experimental tower study, depending on the type of data that was desired. Dry-tray pressure-drop runs were made by blowing air to the bottom of the tower and measuring the differential pressure drop across each tray section. During the measurement of dry-tray pressure drop no water was present on any of the trays. Downcomers were sealed by filling seal pots with water.

Bubble-cap-tray hydraulic data, pressure drop, seal-pot level, and downflow static and froth levels were obtained by blowing air to the bottom of the tower at a predetermined Pitot reading. Water was introduced in the seal pot of the top tray. The pressure drop across each tray was measured by differential manometers, as was the downflow static level. Downflow froth heights were measured visually.

Normally the air flow was set at the lowest value of interest and the liquid flow was increased in steps from 300 to 18,000 gal./hr. Readings were taken, usually, at the following water rates: 300, 1,000, 1,800, 4,000, 6,000, 9,000, 12,000, 15,000 and 18,000 gal./hr. This series of observations was then repeated for several higher air rates, up to the maximum capacity of the blower.

Entrainment data were obtained by measuring the water which was collected on the top tray. For this type of operation water was pumped to the middle tray, the top tray acting solely as an entrainment collector. Air and water rates were varied in a manner similar to the tray hydraulic operation. Only two entrainment measurements were required at each condition since reproducibility of the results was excellent. In many instances successive measurements of entrainment rates were made. Analyses of these weighings (twenty-eight conditions consisting of four quadruplicates, ten triplicates, and fourteen duplicates for a total of forty-six degrees of freedom) show the observed standard error of measurement about each mean to be 3.6%. Therefore 95% of single measurements should be within ±7.2% of the correct weight, and 95% of the means of duplicate measurements within ±5.1%. The value of entrainment shown in the data is the average of the measurements made at any given condition.

The air rate necessary to make all caps bubble, as well as all slots of all caps bubble, was also determined with three operating trays. At a fixed water rate the air rate was varied to determine the bubbling from the cap slots. The opening of the slots of the caps on either side of the tower was observed.

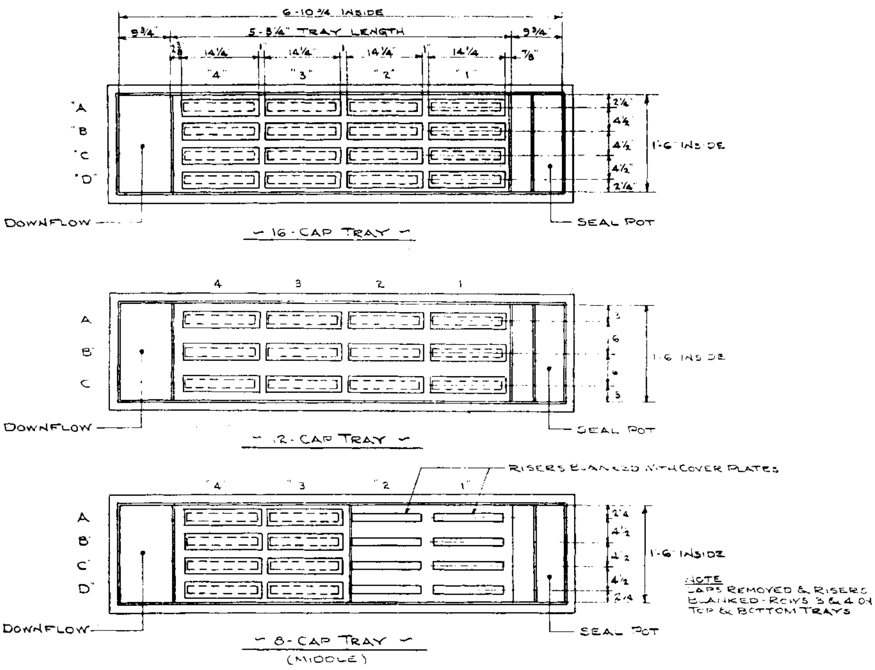

Fig. 3. Detail of trays.

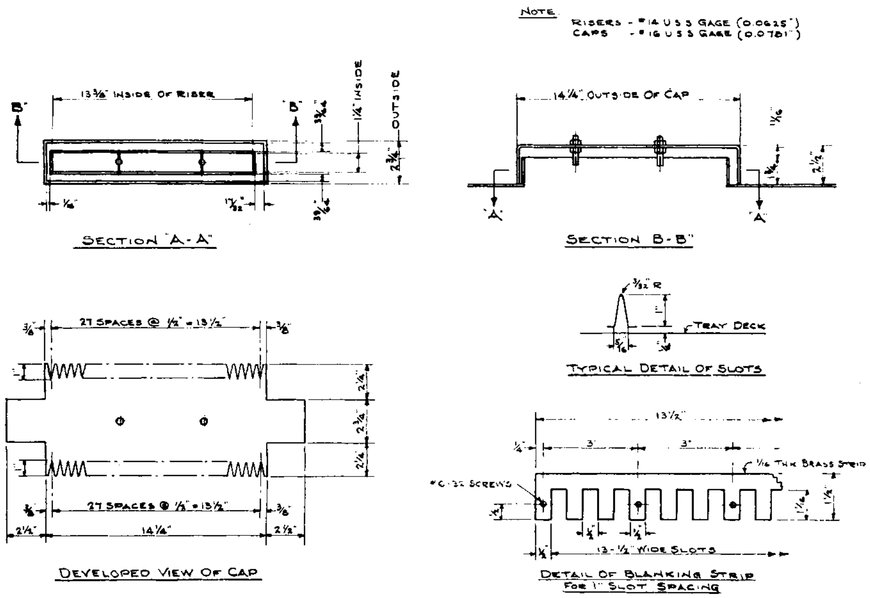

Fig. 4. Detail of rectangular bubble cap.

RESULTS

Bubble-cap-tray Hydraulics

Bubble-cap-tray hydraulics were studied in the experimental tower to obtain the various factors which determine capacity and stability. The capacity of a tray is determined primarily by the height of froth which can exist in the downcomer without causing flooding. Satisfactory bubbling of cap slots usually gives a good indication of tray stability. All the data presented on bubble-cap-tray hydraulics were obtained with trays on 24-in. tray spacing.

When vapor distribution becomes unbalanced because of the hydraulic gradient, there is set up a cross flow of vapor from the downstream end to the upstream. This cross flow would flood a tray well before the flooding loads predicted by existing theory. Houghland and Schreiner (*5*) showed the existence of this behavior with a tray having no support beam. The magnitude of the effect of vapor cross flow is not predictable. Observations from one- or two-tray tests applied to multitrays would be in error if this effect were cumulative. The data presented on pressure drop, froth height, and entrainment show that this unbalance was not important on a 24-in. tray spacing in the test tower; therefore, the data are as correct for an infinite number of trays as for one.

The pressure drop across a bubble-cap tray is fundamentally the most important factor determining tray operation. Excessive pressure drop through bubble caps will result in tower flooding due to backup of liquid in the downcomers. Too small a pressure drop will result in inactive caps (caps not bubbling) and may permit liquid dumping through the risers at high liquid rates. These conditions will affect the tray efficiency adversely by allowing vapor by-passing and a decrease in contact between the vapor and liquid.

Tray capacity is limited by the amount of liquid a downflow can handle. As liquid flows over the downflow weir, vapor is entrained into the downflow. This entrained vapor lowers the density of the downflow liquid. When downflow froth level reaches the top of the downflow weir, pressure drop across the tray increases rapidly and the tray floods. The height of aerated liquid (froth height) which exists in the downflow under any vapor and liquid load is therefore important to the tray designers. This height can be obtained only if a relationship is known between the static liquid and aerated liquid heights in the downflow. The static liquid height is equal to the sum of the seal-pot liquid level, the tray pressure drop, and the loss due to flow through the downflow. This last item is negligible for all practical purposes.

In order to obtain good contacting between vapor and liquid, as well as stable tray operation and uniform froth distribution over a tray, there is a minimum vapor velocity below which a given bubble-cap tray should not be operated. Operations below minimum vapor velocity usually result in a decrease in contact between vapor and liquid. Owing to the liquid gradient over any bubble-cap tray, the vapors have a greater tendency to flow across the downstream end of the tray, thus by-passing the upstream end of the tray. Under heavy liquid loads and low vapor rates, liquid dumping (leakage) can occur from the upstream risers. Such a condition can have serious effects on tray efficiency. Vapor velocities are expressed as Z_F or Z_R, that is, as the ratio of the vapor velocity in the tray free area or riser area, feet per second, to allowable velocity. Souders and Brown (*11*) derived an allowable velocity for reasonable entrainment as equal to $c(\rho_L - \rho_V/\rho_V)^{1/2}$ where c was an arbitrary constant different for each tray spacing. Designers have come to use less conservative values for c and to apply the allowable velocity to the free area (or bubbling area) of a tray, rather than to the superficial area. Converting Souders and Brown's original relationship to linear velocity at a 24-in. tray spacing and taking free area as 80% of the tower area yields an allowable velocity in the free area of 0.227 $(\rho_L - \rho_V/\rho_V)^{1/2}$. The ratio of actual velocity through the free area of a tray to allowable velocity, 0.227 $(\rho_L - \rho_V/\rho_V)^{1/2}$, is designated as Z_F. The ratio of riser velocity to allowable velocity, 0.227 $(\rho_L - \rho_V/\rho_V)^{1/2}$, is designated as Z_R.

Dry-tray Pressure Drop

At various times during the experimental program dry-tray pressure drop was measured for the sixteen-cap tray and the twelve-cap tray with cap slots on ½-in. spacing (56 slots per cap) and also for one tray with cap slots on 1-in. spacing (28 slots per cap). One-inch slot spacing was obtained by blanking off every alternate slot on all the caps of the middle tray. Details of the blanking strips are shown on Figure 4. Figure 5 shows the plot of dry-tray pressure drop in inches of water against air rate expressed as a

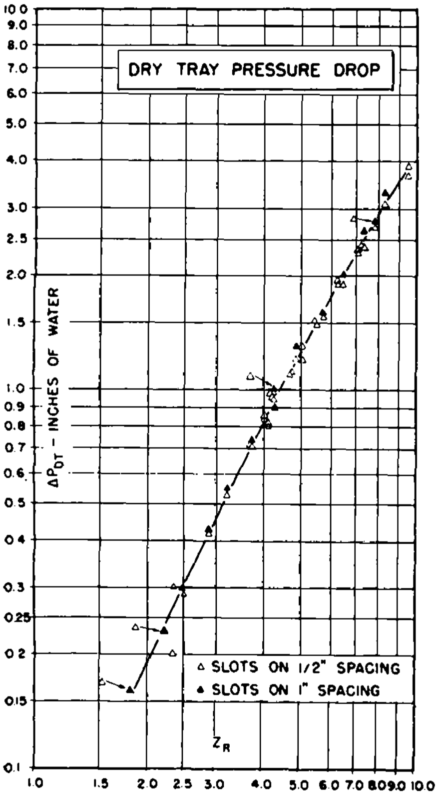

Fig. 5.

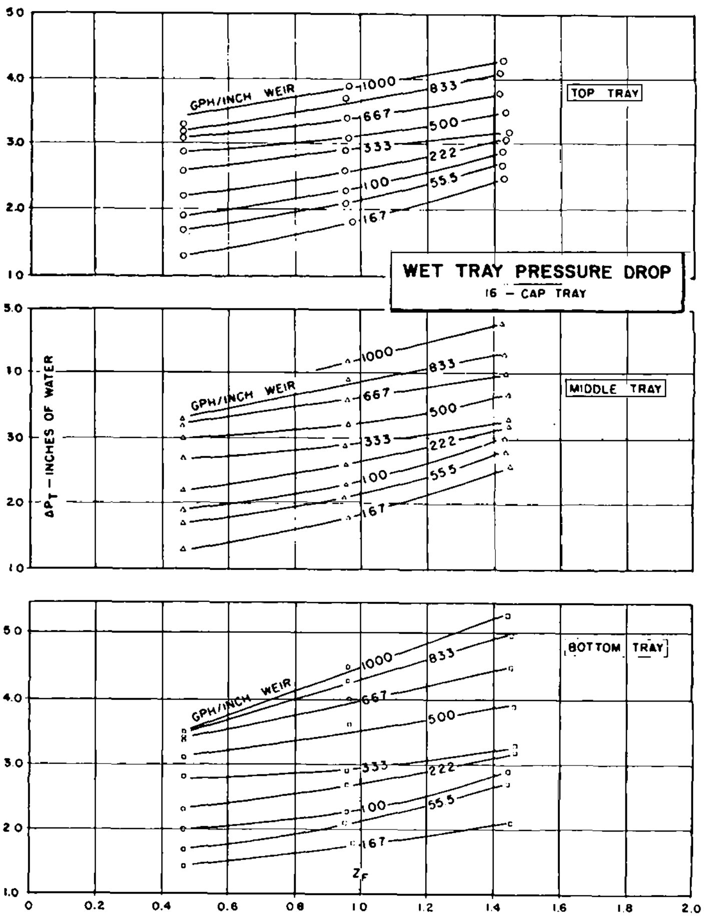

Fig. 6.

Table 1. Tray Details

	16-Cap Tray	12-Cap Tray	8-Cap Tray
Dimensions of downflow from tray			
Upper section	←	$9\frac{3}{4} \times 18$ in.	→
Lower section	←	$5\frac{1}{2} \times 18$ in.	→
Height of downflow weir above tray	←	$1\frac{3}{4}$ in.	→
Height of seal-pot dam above tray	←	$2\frac{1}{4}$ in.	→
Size of risers	←	$1\frac{1}{4} \times 13\frac{3}{8}$ in.	→
Height of risers above tray	←	$1\frac{3}{4}$ in.	→
Size of caps	←	$2\frac{3}{4} \times 14\frac{1}{4}$ in.	→
Number of slots per cap	←	56	→
Number of slots per tray	896	672	448
Tray "free" area, sq. ft.	← 7.906 →		4.10
Total area per tray, sq. ft.			
Inside riser	1.858	1.391	0.929
Riser reversal	2.14	1.60	1.07
Riser annular	1.993	1.492	0.997
Slots alone	1.50	1.12	.075
Below slots and teeth	0.793	0.594	0.397
Clearance between caps			
Long side	$1\frac{3}{4}$ in.	$3\frac{1}{4}$ in.	$1\frac{3}{4}$ in.
Short side	←	1 in.	→

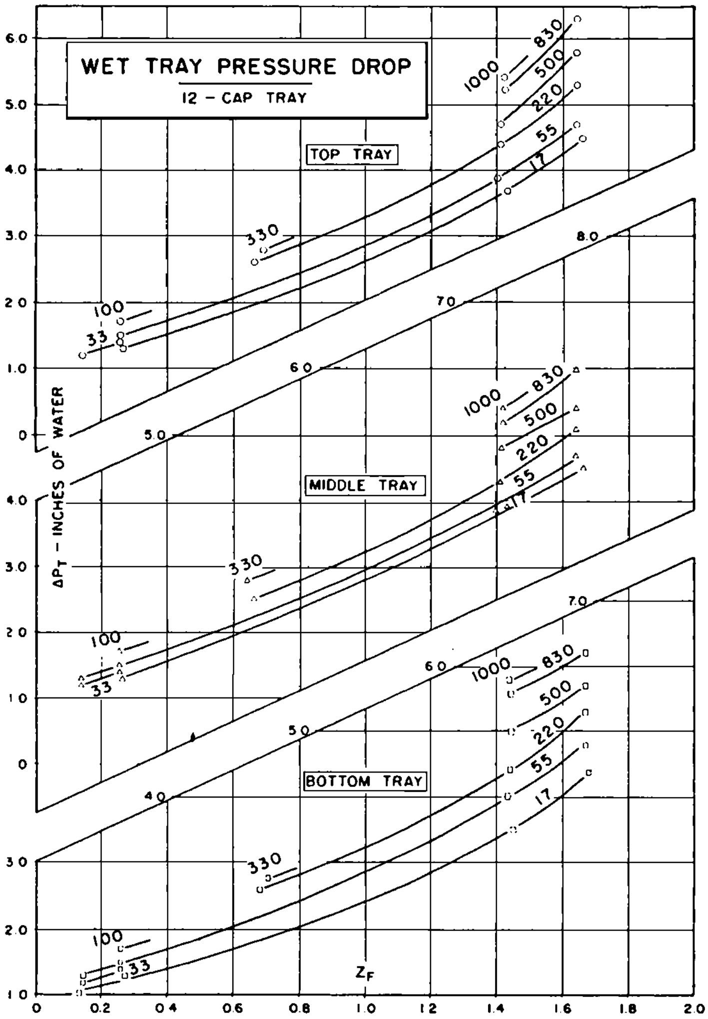

Fig. 7.

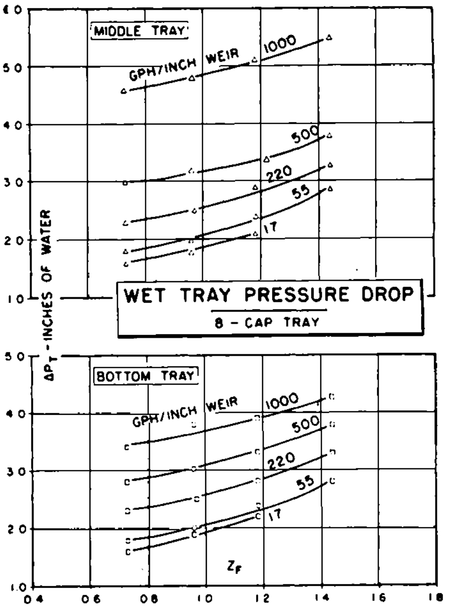

Fig. 8.

percentage of an arbitrarily defined allowable velocity. It can be seen from Figure 5 that the differences in dry-tray pressure drop between a tray with cap slots on ½-in. spacing and one with cap slots on 1-in. spacing are negligible.

Wet-tray Pressure Drop

Pressure drop was measured in the experimental bubble-cap tower with a dynamic air-water system. Figure 6 is a plot of the total pressure drop across each of the three trays for the sixteen-cap tray. Details of this tray are given in Table 1. A cross plot of these data at Z_F of 1.4 and 1.0 indicates that pressure drop for the three trays is about equal up to 400 gal./(hr.)(in. of weir). Above this value the bottom tray has a higher pressure drop than either the middle or the top tray. The top tray has the lowest pressure drop. At a Z_F of 0.5 the pressure drop across the bottom tray is the highest at all liquid rates; the top tray the lowest. Pressure drops across the three operating bubble-cap trays have to be reported individually in this study, owing to the vapor distribution which is different for the three trays. This is indicated by differences in pressure drop under certain vapor and liquid rates. Data (*6*) taken with a static liquid level on the trays gave identical pressure-drop readings across all trays, showing that vapor distribution was excellent. Figure 7 shows the pressure drop for the twelve-cap tray arrangement; Figure 8, for the eight-cap tray arrangement. Details of the twelve- and eight-cap trays are also given in Table 1.

Downflow Level

In order to obtain a relationship between the height of static liquid in the downflow and the height of froth, the static and froth downflow levels were measured for the sixteen-cap tray operation at various air and water rates. Downflow static level was measured by installing a gauge glass at the bottom of the second tray seal pot; downflow froth level was measured visually. All measurements were made from the tray floor. Downflow static level was measured by a gauge glass open to the atmosphere. The correct static level reading was obtained by subtracting from the observed gauge reading the pressure drop across the splash baffles. Figure 9 shows the variation of downflow static and froth heights with air and liquid loading. As it is possible to calculate the unaerated liquid backup, if the pressure drop across the tray and the liquid level in the seal pot are known, downflow froth height can be obtained if the ratio of static height to froth height is known. This ratio is also equal to the froth density divided by the liquid density and gives a measure of the amount of vapor which is present in the downflow. Figure 10 shows a plot of the ratio of static height to froth height against water rate at three air rates. It can be seen that the ratio decreases very rapidly with increasing water rates, indicating that, owing to increasing amounts of entrained air in the downflow, froth height is increasing rapidly. At lower water rates the ratio approaches 1 as a limit. This figure also shows the effect of air rate on the static-to-froth-downflow-height ratio. At a constant water rate the ratio would pass through a minimum which would occur at about a Z_F of 0.96. The scattering of the data in Figure 10 is due to the difficulties of measurement. The accuracy of the visual measurement of downflow froth height and the gauge readings of static downflow height is about $\pm 10\%$.

Seal-pot Level

Figure 11 presents a plot of seal-pot level vs. water rate for three air rates for the sixteen-cap tray. This figure gives the froth level on the upstream side of the seal-pot dam for the middle tray. It can be seen from this figure that seal-pot level varies with air rate, as well as with water rate. It can also be noticed that a common curve could be used for Z_F's from 0.95 to 1.44 without too great an error. Seal-pot level, as measured in this study, is the actual height of liquid upstream of the seal dam. A portion of this curve, up to about 330 gal./(hr.)(in.), is a solid liquid level. Observation of tray operations has shown that at the lower liquid rates no vapor is trapped in the downcomer. Vapor entrained in the downcomer disengages and returns to the vapor space. At higher liquid rates vapor is carried under the downflow plate. Under these conditions liquid in the seal pot has a lower density than the unaerated liquid. This gives an increase in seal-pot level. As downflow-froth levels are calculated on the basis of unaerated liquid in the seal pot, portions of the curves on Figure 11 cannot be used in calculating backup in the downflow. For this study, as downflow static height has been measured, the seal-pot level (unaerated) can be calculated; it is equal to the downflow static height minus the pressure drop across the tray above.

Minimum Vapor Rate

Two minimum vapor rates were recorded for the sixteen- and the eight-cap trays: (1) the air rate to maintain at least one slot on every cap bubbling and (2) the air rate to maintain all slots of all caps bubbling. For the twelve-cap tray the latter condition was obtained. These data are shown on Figures 12, 13, and 14. It can be seen from these figures that the middle tray requires the lowest air rate to obtain cap bubbling and that the bottom tray needs the highest. Figure 15 is a plot of the minimum air rate to maintain all slots of all caps bubbling for the eight-, twelve-, and sixteen-cap trays. This figure shows that minimum air rate depends on the length of liquid travel. A greater air rate is needed for the sixteen-

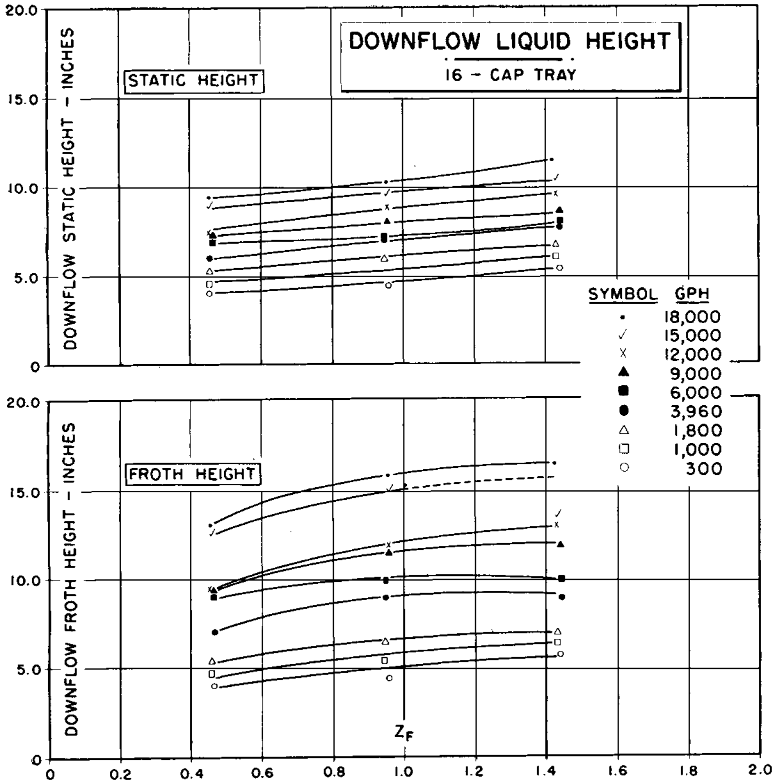

Fig. 9.

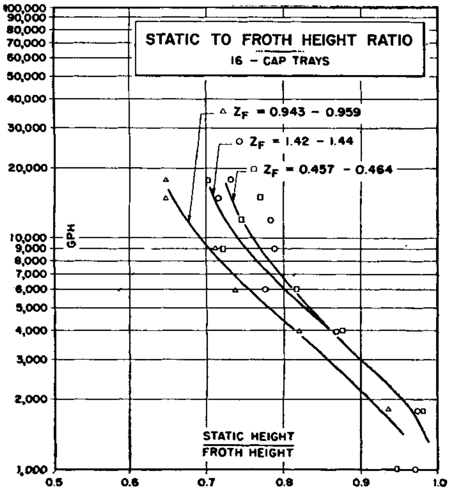

Fig. 10.

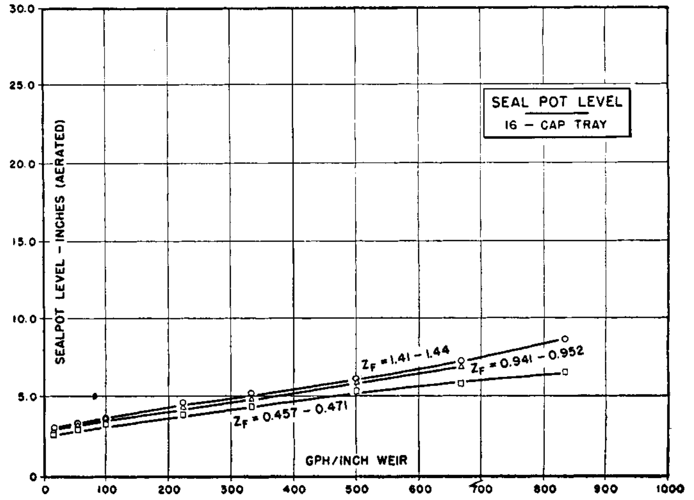

Fig. 11.

cap tray than for the eight-cap tray at the same water rate. This figure also shows that at the same length of liquid travel placing caps on a greater cap spacing has lowered the air rate at which all slots of all caps are bubbling.

Entrainment

In recent years the study of entrainment has become more and more important as the design of fractionating towers has become more competitive, necessitating operation at higher vapor and liquid loads.

Entrainment has been shown theoretically to be a factor in limiting good fractionation. Colburn (*3*) has shown that the effect of entrainment in a plate column is to reduce the apparent efficiency to a new value, according to the equation

$$\frac{E_v}{1 + [(eE_v)/(L/V)]}$$

A tower can be designed to operate at any tray spacing if sufficient trays are added to compensate for the adverse effects of entrainment on efficiency and if the tray is given sufficient capacity to handle the liquid and vapor loads. Some towers can operate with considerable entrainment without any appreciable effect on the efficiency of fractionation (towers with low apparent efficiency operating under high reflux ratios), and other towers can sustain only a small amount of entrainment without a considerable lowering of efficiency (towers with high apparent efficiencies operating under low reflux ratios). In order to obtain the most economical tower design and a tower that will do the fractionation that is required, a judicious choice of tower diameter, tray spacing, and number of trays must be made. The most important factor which influences this choice is entrainment.

Entrainment was studied in the experimental tower with an air-water system using three rectangular-cap bubble trays. Water was pumped to the seal pot of the middle tray, and air was blown under the bottom tray; the top tray was used for the collection of entrainment, which was withdrawn from the seal pot and measured. Wall effect, although not a function of the method of measuring entrainment, was investigated simply by inserting a false wall the full length of the tray so that only three longitudinal rows of caps were active instead of the four rows normally present on the test tray. Thus a significant change in the ratio of wall space to tower volume was effected, but the measured entrainments were not significantly different.

Effect of Length of Liquid Path

Entrainment was measured for the sixteen- and the eight-cap trays. The eight-cap tray was obtained by removing eight caps from the sixteen-cap tray and blanking the risers. Plastic weirs and

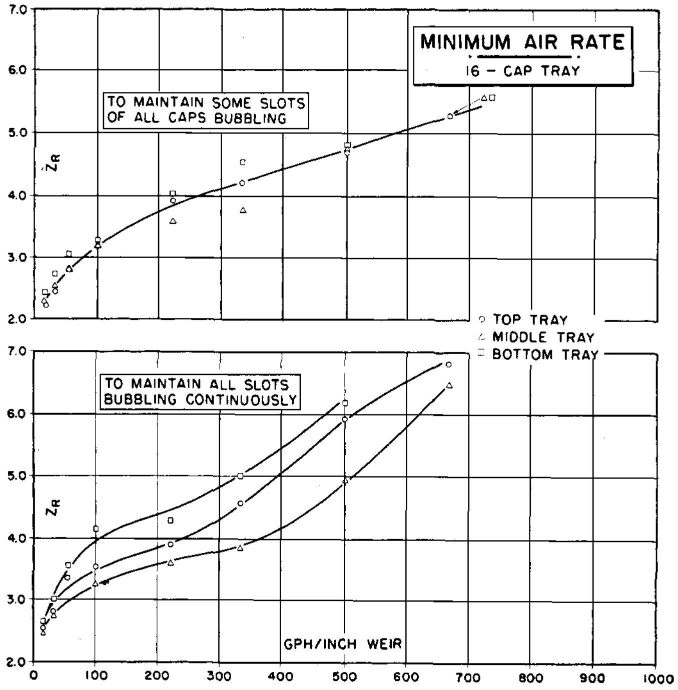

Fig. 12.

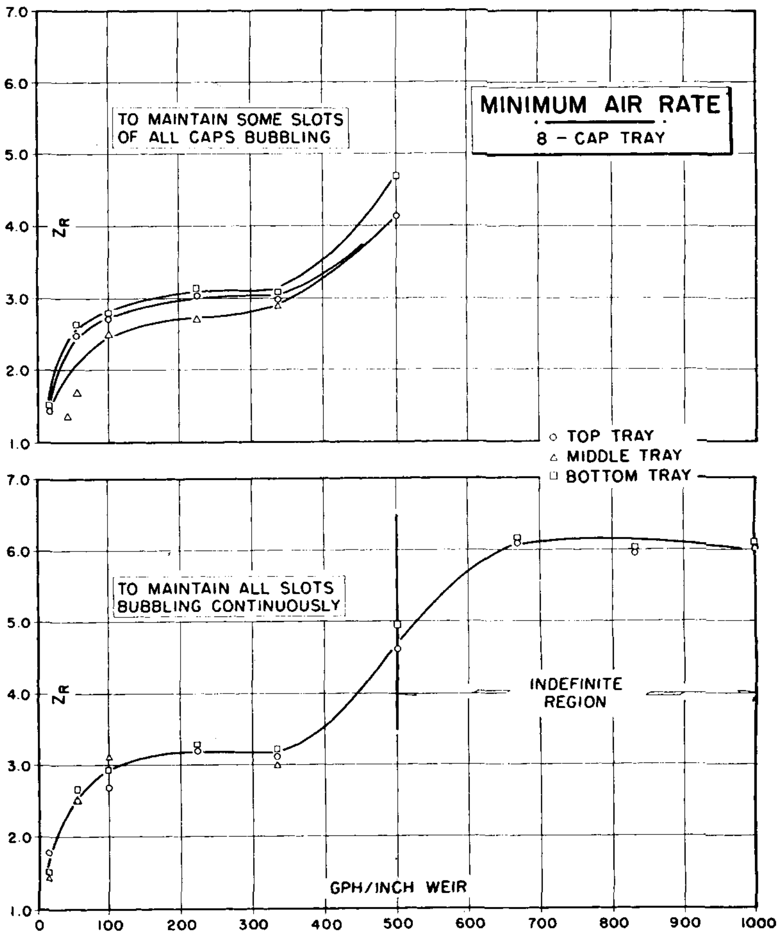

Fig. 13.

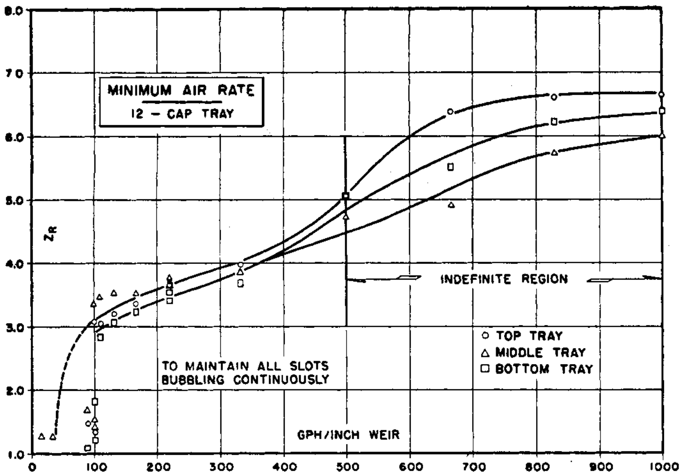

Fig. 14.

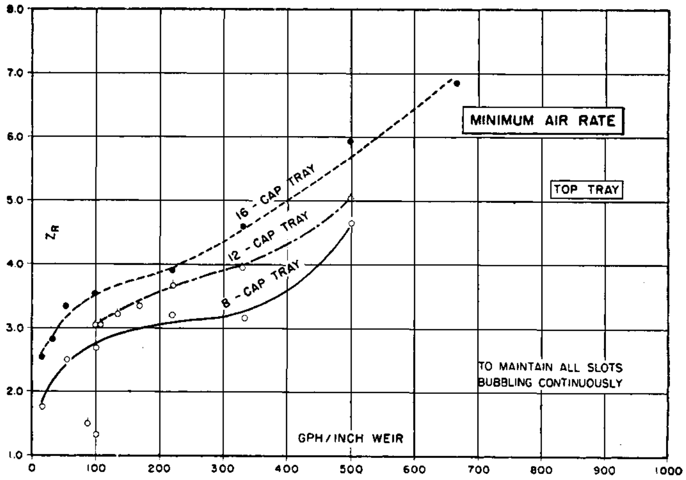

Fig. 15.

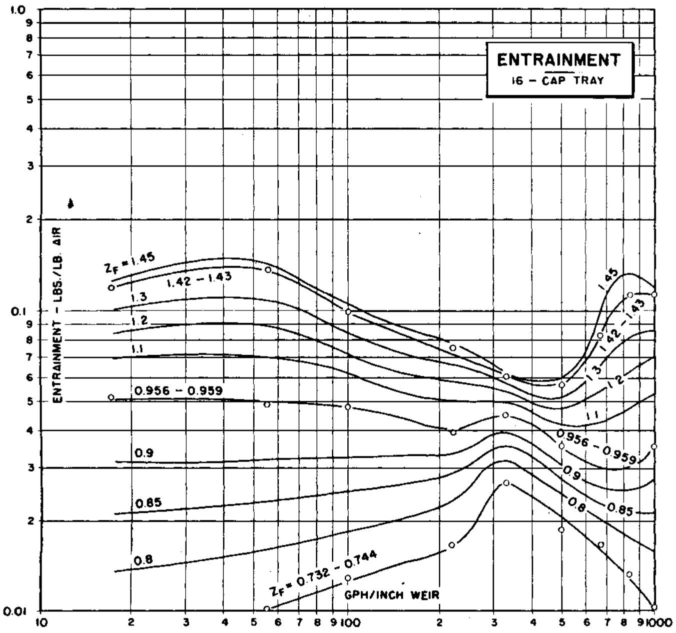

Fig. 16.

seal-pot dams were added to the trays. Figure 16 shows the effect of liquid rate on entrainment at air rates from a Z_F of 0.75 to 1.45 for the sixteen-cap tray. This series of curves contains all the actual measurements, as well as values obtained from a cross plot of entrainment vs. air rate expressed as Z_F. Values of entrainment were obtained at three air rates and nine water rates. As can be seen from the plot of the data, the shape of the curves at the three air rates studied is well defined and the cross plot is used solely to interpolate among the data in order to obtain a series of curves that can be used for obtaining entrainment at any air and liquid rate. The maximum air rate obtained was a Z_F of 1.43. The maximum Z_F obtainable was limited, not only by the capacity of the blower, but also by the amount of pressure the Lucite tower could withstand. It can also be noticed from Figure 16 that there is a definite minimum which occurs at a water rate of about 500 gal./(hr.)(in.) at Z_F's of 1.1 to 1.43. Some of the curves below a Z_F of 1.1 have both a maximum and a minimum. No satisfactory explanation is available for this behavior.

Figure 17 gives a plot of data for entrainment from the eight-cap tray, as well as the lines at other air rates obtained from a cross plot of entrainment and air rate. Figure 18 is a plot of entrainment vs. water rate for the sixteen- and eight-cap trays for Z_F's of 1.38, 1.135, and 0.922. The curves for the sixteen-cap tray were obtained from cross plots; the lines for the eight-cap tray, from the data. It can be seen from Figure 18 that there is an appreciable difference in entrainment between a tray with a length of path of 63 in. and one with 30 in. The tray with the shorter length of liquid path has higher entrainment for a Z_F of 1.38 and 1.135 at all water rates. At a Z_F of 0.922 the eight-cap tray generally has lower entrainment. It can be noticed that as air rate is increased, the difference in entrainment between the sixteen- and the eight-cap trays also increases.

Effect of Slot Spacing

In order to study the effect of slot spacing on entrainment, alternate slots on all caps of the middle tray of the sixteen-cap tray were blanked. The blanking of these slots decreased the number of open slots on the middle tray from 896 to 448. The details of the metal blanking strips are shown in Figure 4. The top and bottom trays remained unchanged and each contained 896 slots per tray. Figure 19 shows the plot of entrainment for the sixteen-cap tray with all slots open and with alternate slots on the middle tray blanked. This figure shows that for Z_F's of 1.43 and 0.955 there are no differences in entrainment between the sixteen-cap tray with or without alternate slots blanked. At a Z_F of 0.72 blanking slots has somewhat increased entrainment, below a water rate of 500 gal./(hr.)(in. of weir).

Effect of Bottom Tray

Entrainment was measured in the sixteen-cap-tray tower with and without caps on the bottom tray in order to determine what effects, if any, the bottom tray had on entrainment from the middle tray. In the first arrangement the caps on the bottom tray were retained. In the second arrangement the bubble caps were removed from the bottom tray, leaving the sixteen risers open. The data for these arrangements are plotted on Figure 20. Only two air rates were studied with caps on the bottom tray: Z_F equal to 0.959 and 0.744. It can be seen from Figure 20 that

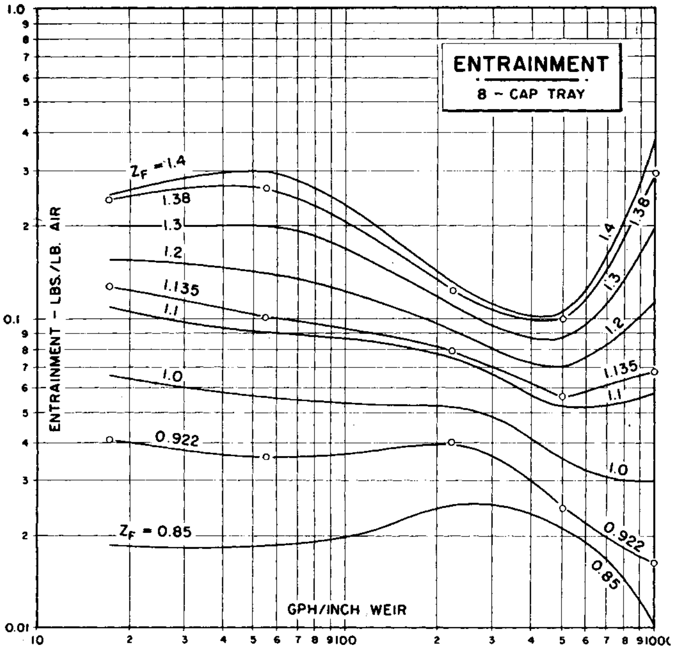

Fig. 17.

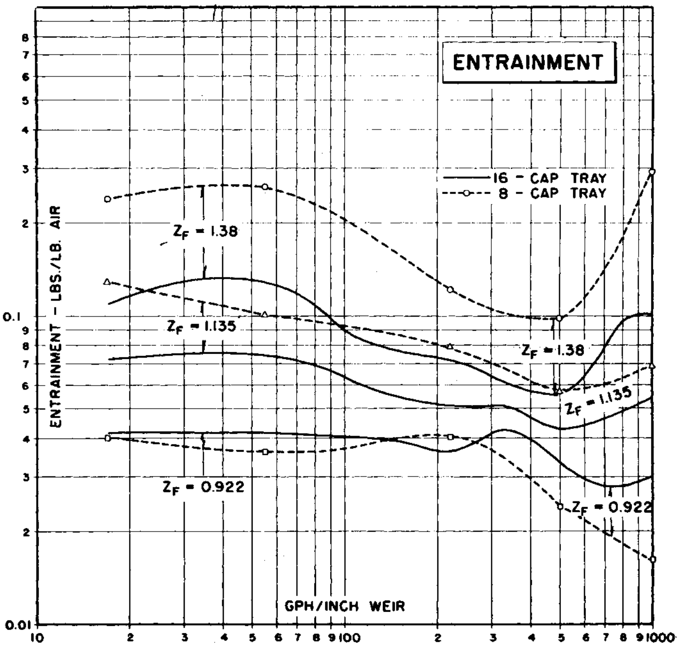

Fig. 18.

removing caps from the bottom tray has had no effect on the entrainment from the middle tray.

Effect of Cap Spacing

Tests were made in the laboratory tower to determine the effect of cap spacing on entrainment. Preliminary tests (*6*) were made by attaching 3/16-in. Lucite strips on the outside of the caps above the slots. These tests indicated that decreasing cap spacing increased entrainment. These Lucite strips reduced the bubbling area between caps and effectively changed cap spacing from 4½ to 4⅛ in. This small reduction of bubbling area increased entrainment substantially. More conclusive tests were made on a bubble-cap tray with twelve caps. This tray had caps on 6-in. spacing, which increased bubbling area from 37.7% of the free area for the sixteen-cap tray to 52.3%. Figure 21 shows a plot of entrainment vs. water rate at four air rates. Curves have also been drawn at various air rates by use of a cross plot. Figure 22 shows comparisons between entrainment with the sixteen-cap tray and the twelve-cap tray at Z_F's of 0.73, 0.968, 1.23, and 1.43. It can be seen that increasing cap bubbling area by increasing cap spacing has decreased entrainment at all air rates and all water rates, except for a Z_F of 1.43 at water rates above 220 gal./(hr.)(in. of weir), where the twelve-cap tray entrainment is slightly higher.

CONCLUSIONS

Although some of the results of this study confirm those previously obtained by other investigators, the following new and basic conclusions on entrainment can be drawn. These are possibly applicable to most bubble-cap-tray designs.

1. Entrainment increases with a decrease in liquid-path length.
2. Entrainment decreases with increasing cap spacing.
3. Decreasing number of slots while maintaining bubbling area constant has negligible effect on entrainment.
4. Increasing or decreasing liquid rate may increase or decrease entrainment, as most entrainment curves have a maxi-

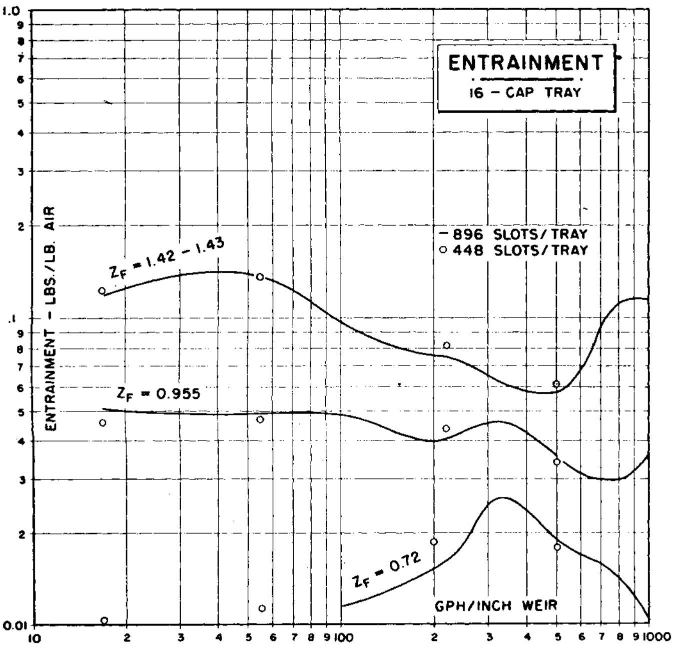

Fig. 19.

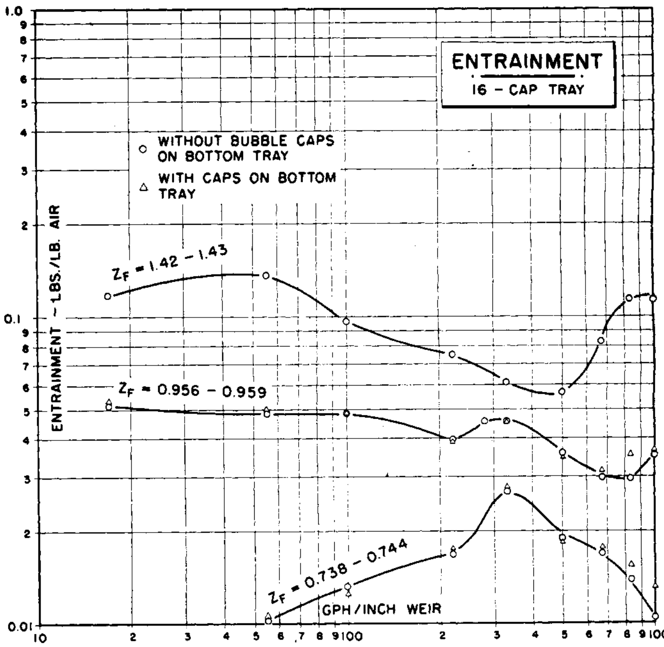

Fig. 20.

mum and/or a minimum at any given air rate.

Owing to the differences in the type of cap used in this study, comparisons with the data of previous investigators would be meaningless and have not been presented. As the conclusions of this study were derived from data taken on a section of a commercial-size tower, they should represent an important contribution to the knowledge of entrainment from bubble-cap trays.

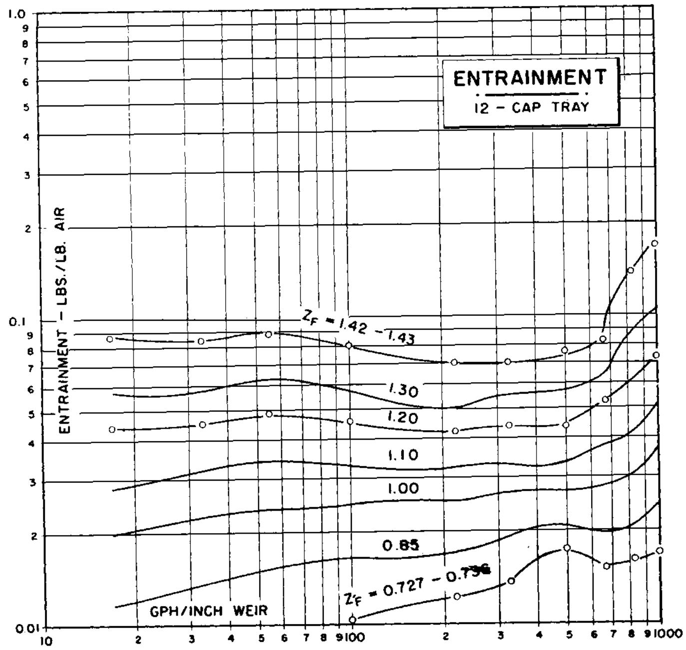

Fig. 21.

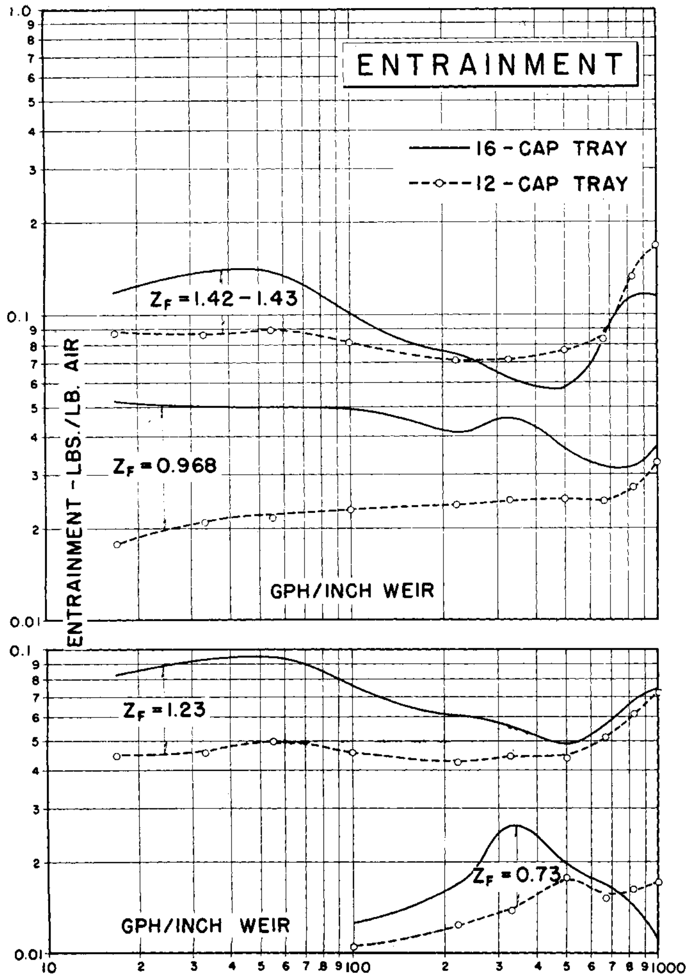

Fig. 22.

ACKNOWLEDGMENT

The authors wish to thank The M. W. Kellogg Company, New York, New York, for permission to publish the data and Walter E. Lobo and Leo Friend for their guidance in preparing the paper.

NOTATION

e = liquid entrainment lb./lb. air

E_a = efficiency with entrainment

E_v = efficiency without entrainment

L/V = reflux ratio, lb. of liquid/lb. of vapor

$$Z_F = \frac{\text{true vapor velocity in free area, ft./sec.}}{0.227\sqrt{\frac{\rho_L - \rho_V}{\rho_V}}}$$

$$Z_R = \frac{\text{true vapor velocity in riser area, ft./sec.}}{0.227\sqrt{\frac{\rho_L - \rho_V}{\rho_V}}}$$

Greek Symbols

ΔP = pressure drop, in. of water

ΔP_{DT} = total dry-tray pressure drop, in. of water

ΔP_T = total wet-tray pressure drop, in. of water

ρ_L = liquid density, lb./cu. ft.

ρ_V = true vapor density, lb./cu. ft.

LITERATURE CITED

1. Ashraf, F. A., T. L. Cubbage, and R. L. Huntington, *Ind. Eng. Chem.*, **26**, 1068 (1934).
2. Chillas, R. B., and H. M. Weir, *loc. cit.*, **22**, 206 (1930).
3. Colburn, A. P., *loc. cit.*, **28**, 526 (1935).
4. Holbrook, G. E., and E. M. Baker, *loc. cit.*, **26**, 1063 (1934).
5. Houghland, G. S., and W. C. Schreiner, *Proc. Natl. Conf. Ind. Hydraulics*, **4**, 75 (1950).
6. Kellogg Company, The M. W., unpublished data.
7. Peavy, C. C., and E. M. Baker, *Ind. Eng. Chem.*, **29**, 1056 (1937).
8. Pyott, W. T., C. A. Jackson, and R. L. Huntington, *loc. cit.*, **27**, 821 (1935).
9. Rhodes, F. H., and P. G. Slachman, *loc. cit.*, **29**, 51 (1937).
10. Sherwood, T. K., and F. J. Jenny, *loc. cit.*, **27**, 265 (1935).
11. Souders, M. J., and G. G. Brown, *loc. cit.*, **26**, 98 (1934).
12. Strang, L. C., *Trans. Inst. Chem. Engrs. (London)*, **12**, 169 (1934).
13. Thomson, A. K. G., *loc. cit.*, **14**, 119 (1936).
14. Volante, M. A., bachelor's thesis, Mass. Inst. Technol. (1929).

Presented at A.I.Ch.E. St. Louis meeting