Perforated Plate Efficiency-Effect of Design and Operating Variables

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Experimental plate efficiency and pressure drop data were obtained on the n-octane–toluene system in a 5 plate, 6 in. diam. column at atmospheric pressure. Hole sizes of 1/16, 1/8, and 3/16 in.; 5.68 and 12.5% free areas; weir heights of 1, 2, and 3 in.; and plate spacings of 6, 12, 18, and 24 in. were studied. Reflux ratios of one, two, four, five, ten, and total were utilized to determine the effect on efficiency.

It was found that hole diameter, free area, plate spacing, and a wide range of reflux ratio had relatively small effect on efficiency and pressure drop; however weir height and lower reflux showed relatively larger effects on both variables.

Efficiencies and pressure drops were lower than those predicted from published correlations particularly at low flow rates.

Mechanical design features of the plates and column and vapor and liquid rates are important variables in establishing distillation column performance. Efficiency correlations in the literature (*2, 12*) include the effects of some physical properties but in general do not include the effects of design features and vapor and liquid rates. Gerster and co-workers (*4, 5, 6, 7*) have related gas film and liquid film efficiencies in terms of liquid retention in the froth on both bubble cap and perforated fractionating plates. The systems studied involved water, water vapor, air, and water, oxygen, and air. The plate diameters were 13 in. and 13 ft. Experimental data on the effects of design and operating variables by using single systems of constant physical properties are needed before techniques of general applicability for estimating plate efficiency can be developed. The effect of design and operating variables on efficiency undoubtedly depends to some extent on system physical properties. Extensive data on a single system can serve to establish the relative importance of the variables and can serve as a basis from which to evaluate the results of less extensive work on other systems.

This investigation covers wide ranges of most of the important design and operating variables on the system n-octane–toluene. Results of an earlier part of this program where column diameters of 1.02, 1.83, and 3 in. were used have been reported (*17, 18*). This investigation was carried out in a 6 in. diam. column and encompassed the variables, reflux ratio, and plate spacing which were not studied previously. Data of the effect of weir height were obtained in the range of usual commercial practice, and additional tests on the effects of hole size and free area were carried out.

As a matter of interest the effect of composition on efficiency data previously reported (*17*) was recalculated after carefully resmoothing the relative volatility data of Berg and Popovac (*1*). The trend showing increasing efficiency with increasing toluene concentration as previously reported was substantiated at low toluene concentrations. However the change in efficiency seems to be less than previously reported, and efficiency seems to be essentially independent of composition in the midrange of concentrations. Similar results on the influence of composition on plate efficiency have been reported by Wijk and Thijssen (*20*), Volland (*19*), and Langdon and Keyes (*11*). At low concentrations of either component or near an azeotrope the low diffusional driving force seems to result in reduced efficiency. Column terminal concentrations were maintained at the same level for each test in this work to eliminate any effect of composition on efficiency.

EQUIPMENT

The column was constructed of 6 in. I.D. glass pipe with accessory equipment (Figure 1). Openings in the insulation were provided to permit visual observation of plate operation. The dimensions of the column and ranges of variables studied are given in Table 1. Free area and downcomer area are in percentage of the column superficial area.

Plate spacing was varied in multiples of 6 in. by using glass pipe sections of appropriate lengths. Downcomers were constructed of 1⅝ in. O.D. copper tubing. The upper ends of the downcomers extended ½ in. above the plates and were machined to allow replaceable circular weirs of various heights to be used. The bottoms of the downcomers extended to within ¼ in. of the plates below. Plate inlet weirs and splash baffles were not used.

Plate layout is shown in Figures 2 and 3. A larger hole spacing was used for the plates of smaller free area, so that

TABLE 1. DIMENSIONS OF COLUMN AND VARIABLES

Column Diameter, in.	6
Plate Spacing, in.	6, 12, 18, 24, 30
Number of Plates	5, 5, 3, 2, 2
Plate Thickness, in.	⅛
Weir Height, in.	½, 1, 2, 3
Hole Diameter, in.	1/16, ⅛, 3/16
Hole Pitch/Diameter Ratio	2, 3
Percentage Free Area of Holes	5.68, 12.5
Percentage Downcomer Area	7.1
Reflux Ratio, L/D	1, 2, 4, 5, 10, total
Vapor Rate	
F_h, Hole F Factor	1 to 15
G, lb./hr.-sq. ft.	100 to 1400

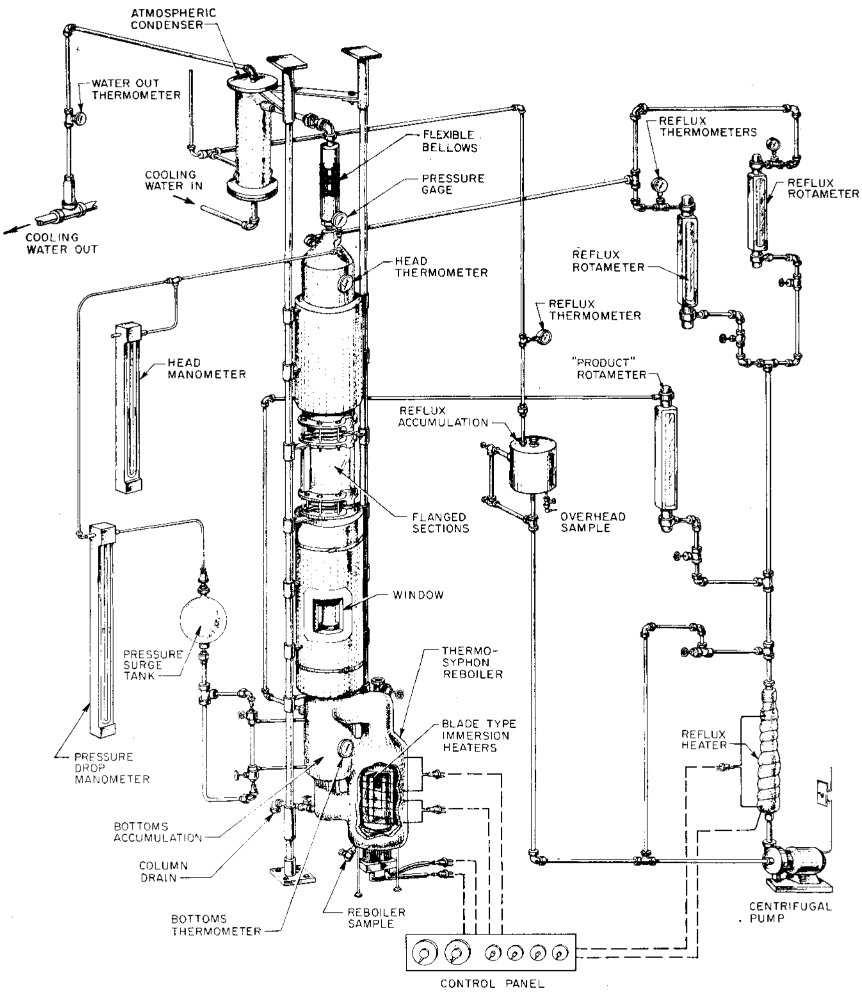

Fig. 1. Distillation column and its accessories.

substantially the same effective plate area was covered by perforations in each case. The holes were drilled on equilateral triangular pitch in all cases.

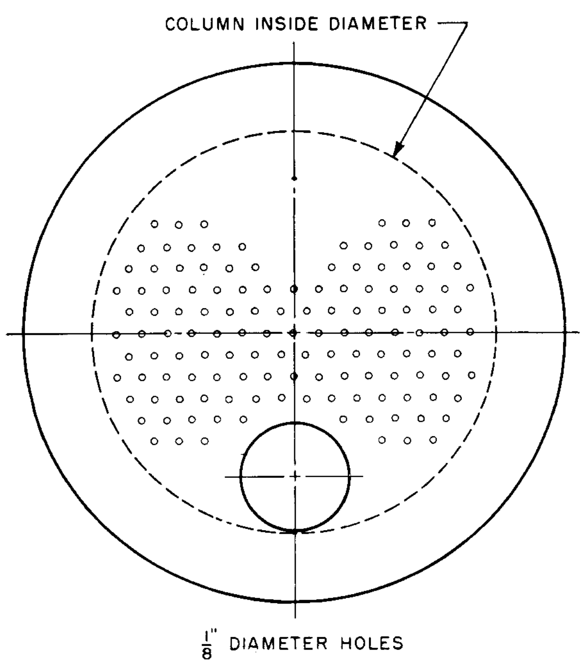

Fig. 3. Perforated plate layout, 5.68% free area.

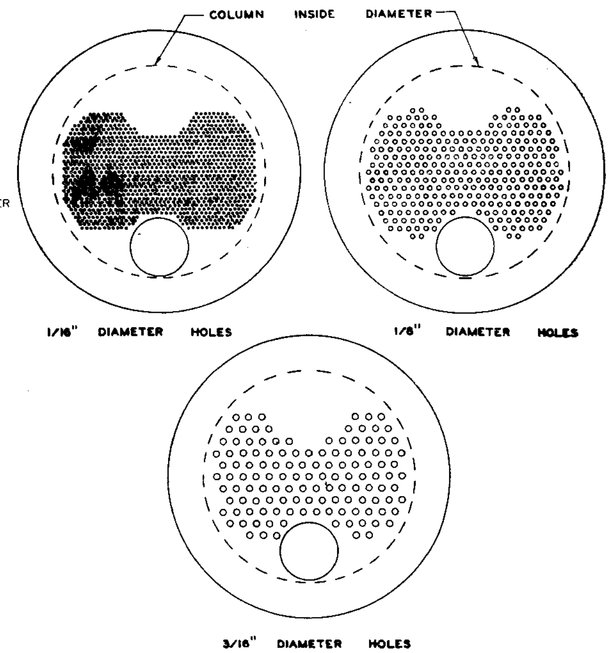

Fig. 2. Hole layout for perforated plates.

PROCEDURE

The n-octane–toluene binary system was used throughout this investigation as the test system. The materials and analytical techniques have been described (*17, 18*).

Results of preliminary column tests showed that steady-state operation could be reached 90 min. after column startup or 30 min. after a subsequent change in operating conditions. To insure steady-state operation $2\frac{1}{2}$ hr. were allowed after column start up, and 1 hr. was

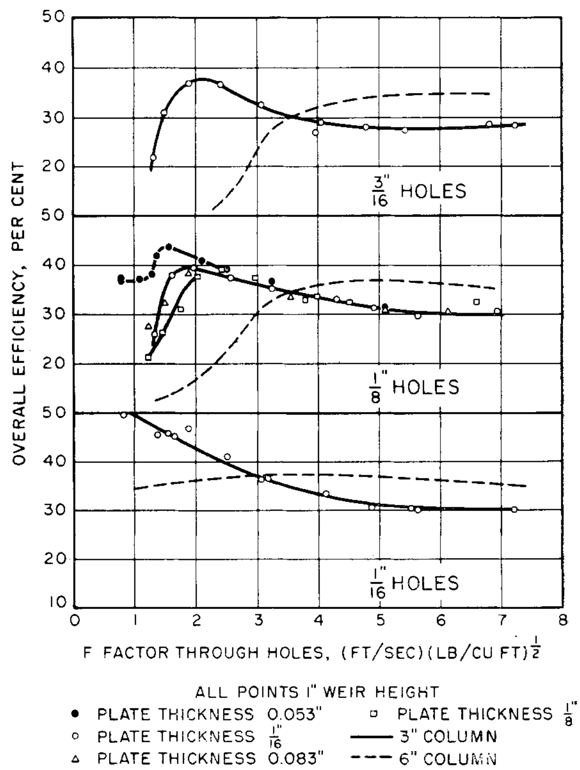

Fig. 4. Comparison of 3 and 6 in. columns.

allowed after a subsequent change in operating conditions beforeo verhead condensate and bottoms samples were taken. A series of runs over the entire range of vapor rates were made after each change in a design variable. The upper limit of column vapor rate was established by the reboiler capacity. In no case was the column flooding point reached. The lower limit of column vapor rate was established by the quantity of reflux or distillate which could be metered effectively.

Weeping was observed to a greater or lesser extent in the case of trays of the larger free area at all vapor rates utilized.

The Smoker equation (*16*) was used in the efficiency calculations for runs at finite reflux, and the Fenske equation (*3*) was used for runs at total reflux; these are consistent in that Smoker's equation reduces to Fenske's equations for the case of total reflux. The two equations are based on assumptions of both constant relative volatility and constant molal overflow. The assumption of constant molal overflow is satisfactory because of the small column temperature gradient and the small difference in heats of vaporization of the two components. The relative volatility varied by as much as 25% between column terminal compositions. For this reason a number of runs were calculated plate-to-plate by using Berg's (*1*) vapor-liquid equilibrium composition data to determine what error might be introduced by assuming constant relative volatility; it was established that no discernible error was introduced. The equations give slightly better reproducibility of results than the plate-to-plate method which requires repeated readings from a chart.

Smoker's equation for the number of theoretical stages required in a rectifying column is

$$n = \frac{\text{Log}\dfrac{(x_d - k)\left|1 - \dfrac{L}{V}\dfrac{[1 + (\alpha - 1)k](\alpha - 1)(x_b - k)}{\left[\alpha - \dfrac{L}{V}1 + (\alpha - 1)k^2\right]}\right|}{(x_b - k)\left|1 - \dfrac{L}{V}\dfrac{[1 + (\alpha - 1)k](\alpha - 1)(x_d - k)}{\left[\alpha - \dfrac{L}{V}1 + (\alpha - 1)k^2\right]}\right|}}{\log \dfrac{L}{V}\dfrac{\alpha}{[1 + (\alpha - 1)k]^2}} \qquad (1)$$

where

$$k = \pm\frac{1}{2}\left\{\left[\frac{1}{\alpha - 1} + \frac{x_d}{L} - \frac{V}{L}\frac{\alpha}{(\alpha - 1)}\right]^2 - \frac{4x_d^{1/2}}{L(\alpha - 1)}\right\} - \frac{1}{2}\left[\frac{1}{\alpha - 1} + \frac{x_d}{L} - \frac{V}{L}\frac{\alpha}{(\alpha - 1)}\right]$$

$$0 < k < 1$$

In the case of total reflux Smoker's equation reduces to the Fenske equation

$$n = \frac{\log \dfrac{(x_d)(1 - x_b)}{(x_b)(1 - x_d)}}{\log \alpha} \qquad (2)$$

One stage was subtracted from the number computed to account for the reboiler. The remainder was divided by the number of actual plates in the column to obtain over-all efficiency.

Vapor densities for use in computing vapor velocities and F factors were calculated by using the ideal gas law at the column average temperature and pressure. Molecular weight was taken as the average of the molecular weight of the distillate and the molecular weight of the vapor in equilibrium with the bottoms product. The compressibility factor of the vapor at column conditions was estimated from charts based on the theory of corresponding states to be about 0.97, which indicates that the error introduced by using the ideal gas law is not significant.

Froth height was observed, but sloshing of the liquid on the plate made accurate determination of froth height impossible. Therefore no complete data were taken with respect to this factor.

RESULTS*

Comparison of 3- and 6-in. Columns

Data obtained from the 3 in. diam. column are shown in Figure 4 and are compared with data derived from the 6 in. diam. column. The efficiency level shown is slightly lower than previously reported (*17*) because of a small difference in relative volatility data used in the calculations (as already noted). The data are for a 6 in. plate spacing, 12.5% free area, and a 1 in. weir height. The only design feature other than diameter, which differs between the two columns, is plate thickness. The 6 in. column utilized ⅛ in. thick plates, whereas the 3 in. column contained plates 1/16 in. thick. Results from a series of tests where the 3 in. diam. column with different plate thicknesses was used are shown on the center chart (solid lines). Plate thickness has no apparent effect on efficiency in the stable operating range, but it does influence the lower limit of effective operation. Thinner plates have a slightly wider range of stable operation. The efficiency obtained from the smaller column rises abruptly to a distinct maximum near the lower limit of operation and then falls to a nearly constant value at higher vapor rates. The maximum efficiency obtained is considerably higher than the nearly constant value obtained at higher vapor rates. The efficiency obtained from the 6 in. column (dotted lines on Figure 4) rises more slowly with increasing vapor rate to a much less distinct maximum.

Except at low vapor rates the larger column is more efficient by about 20% (6 to 7 absolute units of efficiency). Kirschbaum (*10*) reported a similar higher efficiency for a 400 mm. diam. column in comparison with a 110 mm. diam. column. Kirschbaum (*10*) and Perry (*14*) attributed the higher efficiency of larger columns to an increase in countercurrent effect. Increasing column diameter increases vapor flow area by the second power but only increases liquid flow area across the plate by the first power. Kirschbaum states that the higher liquid velocity and longer liquid path both reduce the effect of mixing of liquid on the plate thereby tending to increase efficiency.

The 3 in. column operates more effectively at lower vapor loads than the 6 in. column. The upper limit of operation should be about the same for both columns with the same plate spacing. The upper limit is established by the pressure drop which causes flooding. Kirschbaum (*10*) also noted a narrower operating range for larger columns with respect to throughput.

Effect of Plate Spacing on Efficiency

Efficiencies were determined at five different plate spacings. The data on Figure 5 are for 12.5% free area plates at a 1 in. weir height with plate spacings of 6, 12, 18, 24, and 30 in. No well defined trend of efficiency with plate spacing over the range of vapor rate and liquid rate tested is apparent. The entrainment rate must be a sufficiently low fraction of the total liquid rate in all cases studied, so that changes in its effect are not detectable within the precision of the work.

Karim and Nandi (*9*) tested three systems at 6 and 12 in. tray spacings. Increasing the spacing greatly increased the efficiency for the carbon tetrachloride-toluene and acetone-water systems but had little effect on the ethanol-water system.

Kirschbaum (*10*) tested the ethanol-water system at 1.97, 3.94, and 7.88 in. spacings. The column efficiency and operating range were markedly improved by increasing spacing from 1.97 to 3.94 in. However the improvement was only

*Tabular material has been deposited as document 5762 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $3.75 for photoprints of $2.00 for 35-mm. microfilm.

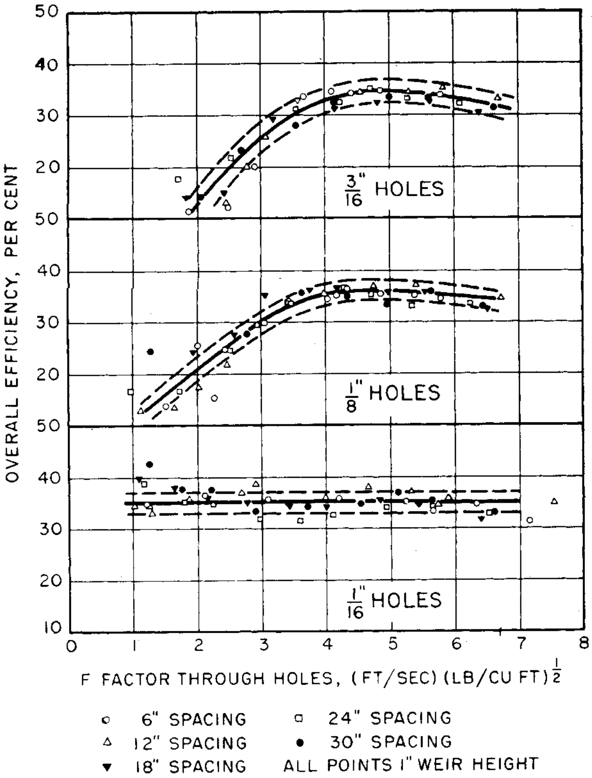

Fig. 5. Effect of plate spacing on efficiency.

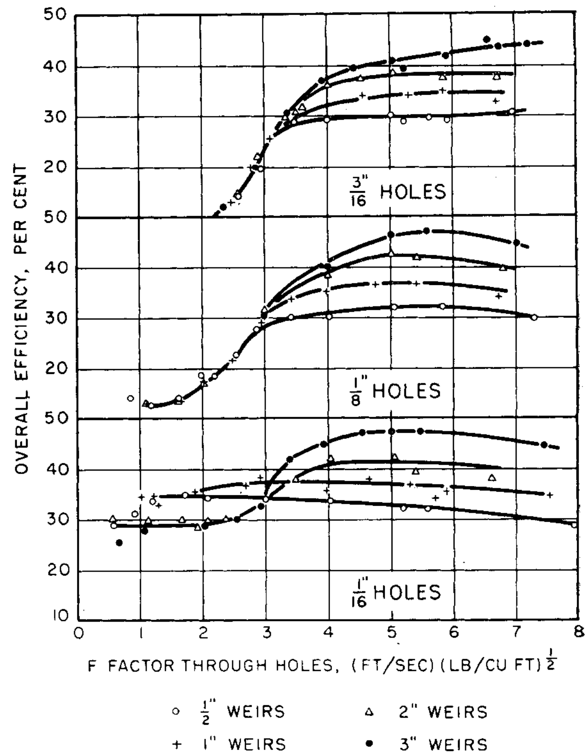

Fig. 6. Effect of weir height on efficiency.

on the order of 3% on increasing plate spacing from 3.94 to 7.88 in. Higher spacings were not tested. It seems likely that little or no change would have been found for spacings above 7.88 in.

As a matter of interest Kirschbaum noted that entrainment is much lower for perforated plates than for bubble cap plates because the higher velocity between bubble caps tends to throw the liquid upward. He attributes the decrease in perforated plate efficiency with increasing vapor rate in the stable operating range to decreased vapor-liquid contact time. His work shows that bubble plate efficiency is much more influenced by plate spacing than perforated plate efficiency.

It may be concluded that for some systems including *n*-octane–toluene plate spacing above 6 in. is not an important

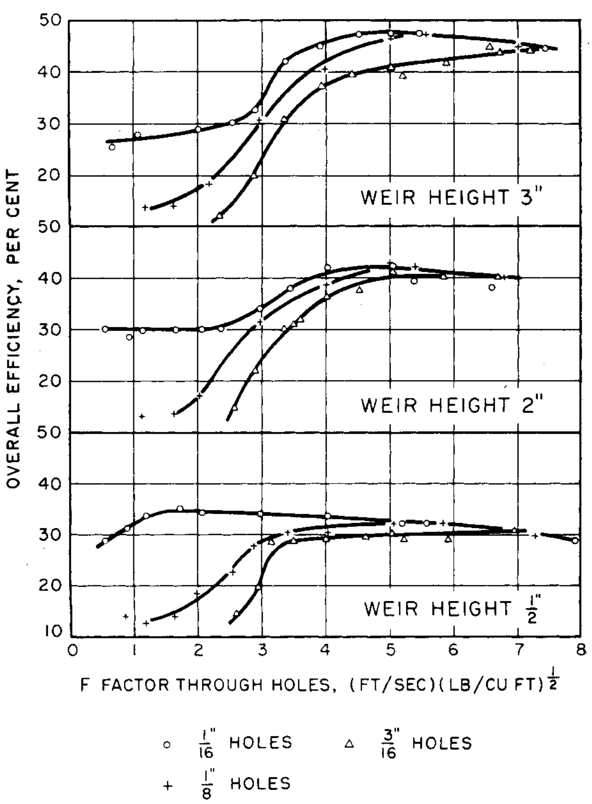

Fig. 7. Effect of hole size on efficiency.

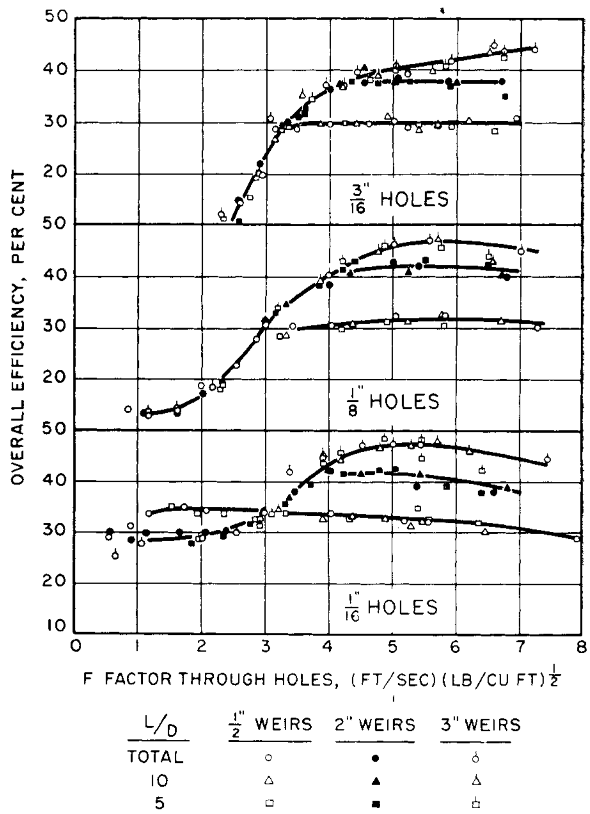

Fig. 8. Effect of reflux on efficiency.

variable over wide ranges of vapor rate. In certain other systems plate spacing is indicated to be of much greater importance.

Effect of Weir Height on Efficiency

Data at weir heights of ½, 1, 2, and 3 in. in the 6 in. diam. column are shown in Figure 6. Increasing weir height from ½ to 3 in. is shown to increase efficiency by about 50% (15 absolute units of efficiency) in the effective operating range. At low vapor rates weir height seems to have no effect except in the case of the 1/16 in. perforations where higher weirs yield lower efficiency. Weir height has no effect when the liquid weeps through the holes as is the case at low vapor rates for plates with ⅛ and 3/16 in. holes. A liquid level was maintained on the plates with 1/16 in. holes at all vapor rates tested. The level was sufficient to cause flow over ½ and 1 in. weirs resulting in less weeping which may account for the inversion of the trend of the curves of efficiency with weir height at low loads on plates with 1/16 in. holes.

Although the experimental results indicate a definite effect of weir height on efficiency, the extent of the effect may be influenced by the lower efficiency level. Further data at various efficiency levels are necessary before this can be proved.

Karim and Nandi (*9*) found that for the ethanol-water system weir heights of 1 and 2 in. gave substantially the same results. Apparently the effect of weir height as well as that of plate spacing varies with system properties.

It is interesting to compare the results of Kirschbaum (*10*) and Peavy and Baker (*13*) who, using the ethanol-water system, studied the effect of static submergence on efficiency of bubble cap plates. Static submergence for bubble plates is analogous to weir height for perforated plates. Peavy and Baker noted systematic increases in efficiency with increasing static submergence over the range 0, ½, 1 and 2 in. Kirschbaum reported no change in efficiency for increasing static submergence over 1 in. An explanation for this apparent discrepancy probably lies in differences in design features other than those involving static submergence.

Effect of Hole Size on Efficiency

The data of Figure 6 are represented in Figure 7 with parameters of hole size at three different weir heights. Smaller hole sizes result in higher plate efficiency at low and moderate vapor rates. Plates of small hole size tend to retain the liquid level required for normal operation even at low vapor rates. For a given free area smaller hole diameter yields greater interfacial area which also tends to increase efficiency. Plates of larger hole size operate unsatisfactorily at low vapor loads. However the effective operating range should extend to a somewhat higher vapor load because of lower pressure drop.

At the highest vapor rates tested all three holes sizes yield substantially the same efficiency, and it is possible to predict from the shape of the curves that, if still higher rates were tested, the plates of largest hole size would operate with highest efficiency. However there are insufficient data at higher vapor velocities to definitely support such a conclusion. It was observed that the liquid on the plate was agitated into a violent side-to-side sloshing at high vapor rates, and that this sloshing was considerably less violent for plates of larger hole size.

Chu and associates (*8*) and Karim and Nandi (*9*) reported effects of hole size similar to those shown in this work.

Effect of Reflux on Efficiency

Results of tests at external or operating reflux ratios of five, ten, and total are shown in Figure 8. Parameters are weir height and reflux ratio at three different hole sizes. Results of the runs at various reflux ratios appear to fall on the same general curves as indicated by the band formed by the dotted lines on Figure 8. Reflux ratio has no discernible effect on efficiency in the range from $L/D = 5$ to $L/D = \infty$.

An additional series of tests was made to determine the effect of reflux ratio over a wider range with respect to relative liquid and vapor flow rates. External reflux ratios used were total, four, two, and one. The additional experimental work was carried out at 1, 2, and 3 in. weir heights on plates of smaller free area, as will be discussed. The curves in Figure 9 indicate that reflux ratios of two or greater yield the same results, but that efficiency is appreciably lower for a reflux ratio of one, particularly at high vapor loads.

The explanation of this effect must lie in consideration of the several factors which influence efficiency. Increasing reflux ratio at a given vapor rate involves only increasing the internal liquid rate, while other factors remain the same. The resulting decreased liquid retention time on the plate tends to reduce efficiency. On the other hand a higher liquid velocity reduces the effect of mixing of the liquid on the plate thereby increasing the countercurrent effect and tending to increase efficiency. Entrainment rate at higher liquid rates becomes a smaller fraction of the total liquid rate causing less concentration change and tending to improve efficiency. Turbulence on the plate induced by higher liquid rates should also tend to improve efficiency. These factors seem to offset each other for reflux ratios above two, while those tending to promote efficiency predominate at lower ratios.

Volland (*19*) reported results on the ethanol-water system in which the effect of reflux on efficiency is in surprisingly good agreement with this work on the *n*-octane–toluene system. Similarly Wijk and Thijssen (*20*) found that for the *n*-heptane–methylcyclohexane system increasing reflux increased efficiency up to an external reflux ratio of about four, above which there was no effect. Kirschbaum (*10*) and Peters (*15*) reported efficiency independent of reflux at relatively high reflux ratios.

Effect of Free Area

The results shown in Figure 9 are for plates of 5.68% free area (solid lines) in comparison with results on plates of 12.5% free area (dotted lines). In addition to free area, plate spacing was varied. An 18 in. spacing was used with the 5.68% free-area plates, whereas a 12 in. spacing was used with the 12.5% free-area plates. However spacing has been shown to have practically no influence on efficiency in the ranges of variables tested, and this can be considered a valid comparison. A greater pitch to diameter ratio was selected for the plates of smaller free area to give perforations over substantially the same effective plate area in both cases.

Reducing the plate free-area resulted in the plate operating effectively even at the lowest vapor rates tested. At the lowest vapor rate essentially all liquid flow between plates occurred as the result of weeping. However in spite of this a liquid depth of about ½ in. was maintained on the plate. This liquid depth was sufficient for good plate operation as evidenced by the efficiency attained.

About the same peak efficiency was reached with the plates of different free areas at all three weir heights. The peak efficiency however occurs at considerably different hole vapor velocities.

The data of Figure 9 are presented in Figure 10 with column superficial mass velocity as the abscissa. This plot is of interest as it shows that efficiency is approximately the same for the plates of greatly different free area at a given column vapor rate, providing the rate is high enough for the 12.5% free-area plates to be in effective operation. Comparison of Figures 9 and 10 indicates that column-vapor mass velocity may be preferable to hole-vapor velocity for comparing plates of different free area. On either basis a higher vapor rate is required to attain good operation of the 12.5% free-area plates. The upper limit of operation of the 12.5% free-area plate should be much higher because of lower pressure drop. Reboiler limitations prevented establishment of the upper limit of capacity in this work.

Volland (*19*) and Foss and Gerster (*4*)

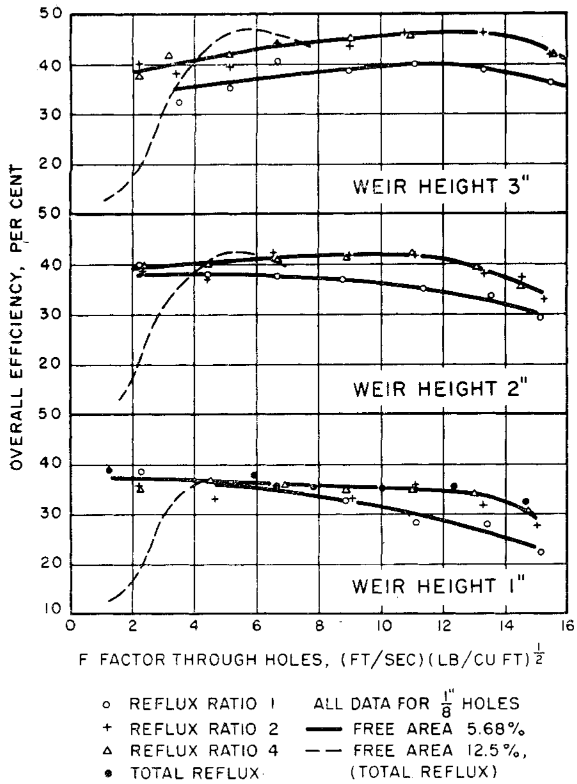

Fig. 9. Effects of free area and reflux on efficiency.

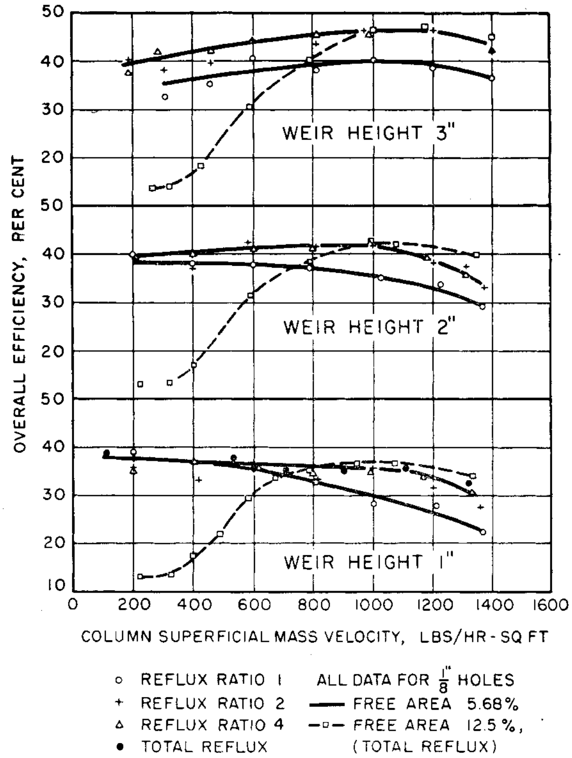

Fig. 10. Effect of free area at various column mass velocities.

investigated the effect of free area and found it to be slight. Both Volland and Foss and Gerster indicated that plates of about 7 to 8% free area yield slightly higher efficiencies than plates of other free areas. Umholtz (*17*) and Karim and Nandi (*9*) noted no effect of free area on efficiency at vapor rates high enough to insure effective plate operation. Umholtz's tests on efficiency variation with free area were carried out in a 1.83 in. diam. column with a $\frac{1}{4}$ in. weir height.

Pressure Drop

The effects of plate variables on pressure drop are in some ways similar to their effects on efficiency. Pressure drop results for the 12.5% free-area plates are shown in Figure 11 for various weir

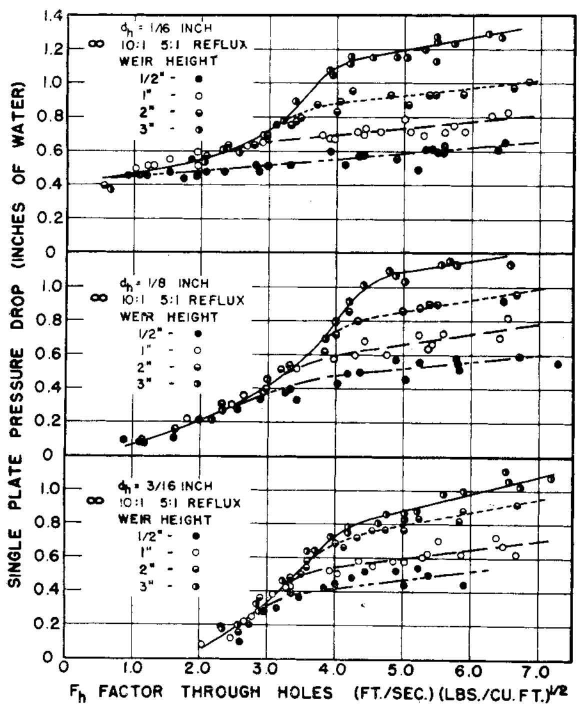

Fig. 11. Effect of hole size and weir height on perforated-plate pressure drop.

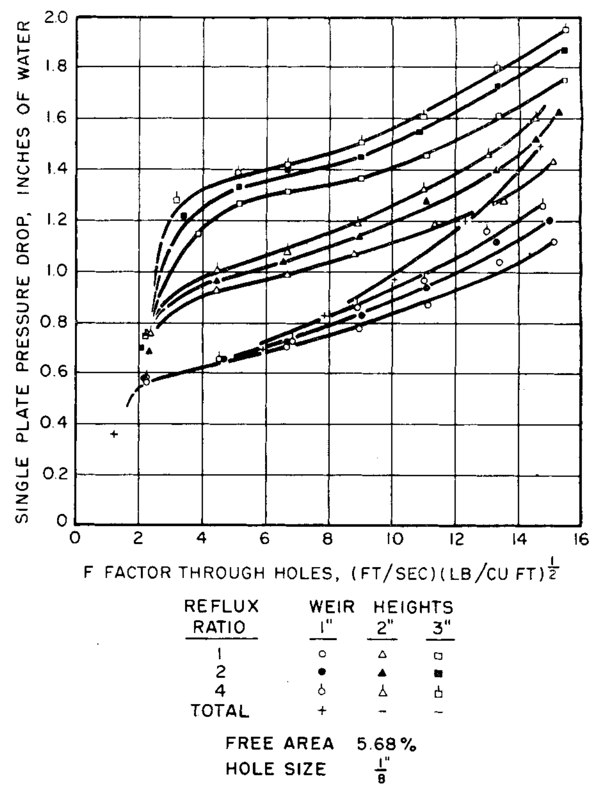

Fig. 12. Effect of reflux and weir height on pressure drop.

TABLE 2.

Variable Studied	Range of Variable	Approximate Effect on Absolute Efficiency Vapor Rate Low	Moderate	High
Column Diameter, in	3, 6	−15 to 30	+5	+7
Place Spacing, in.	6, 12, 18, 24, 30	0	0	0
Weir Height, in.	½, 1, 2, 3	0	+10	+15
Hole Diameter, in.	1/16, ⅛, 3/16	−20	−4	0
Free Area, % of column superficial area	5.68, 12.5	−26	0	+3
Plate Thickness, in.	0.053, 0.063, 0.083, 0.125	−18	0	0
Reflux Ratio, L/D	1, 2,	0 to +5	+5	+5
	4, 5, 10, total	0	0	0
Feed (Reboiler Toluene Concentrations)	13, 21	+1	+1	+1
Mole %	21, 46	0	0	0

heights, hole sizes, and reflux ratios. Plate spacing is not shown as a parameter because it did not influence results within the precision of the work. Reflux ratio also seems to have little effect on pressure drop. Larger hole size resulted in lower pressure drop for a given total hole area, and higher weirs resulted in higher pressure drop.

Pressure drop results for the 5.68% free-area plates are shown in Figure 12. Parameters are weir height and reflux ratio. These plates of smaller free area operated with good efficiency over the entire range of vapor rates tested. The pressure drop at a given vapor rate was much higher than that for the plates of larger free area. This higher pressure drop maintained a satisfactory liquid level on the plate, so that effective operation was obtained even at low vapor rates. Increasing liquid rate (at the same vapor rate) caused by increasing reflux ratio increased pressure drop. Such a trend probably also existed in the case of the 12.5% free-area plates, but pressure fluctuation reduced the precision of the measurements so that the trend was not apparent. Extensive weeping was observed in the case of the larger free-area plates at all vapor rates tested.

GENERAL DISCUSSION

The efficiency range of 30 to 45% encountered in this investigation is lower than that predicted from the correlations of Drickamer and Bradford (*2*), which indicates an efficiency of 63%, and of O'Connell (*12*), which indicates an efficiency of 65%. These correlations relate in one case the molal average viscosity of the system with efficiency and in the other the product of the molal average viscosity and relative volatility with efficiency and do not include other system, operating, and design variable effects.

Possibly lower efficiencies could be encountered here because of the weeping of liquid through the holes, particularly at low vapor rates and for the larger free-area plates, possibly because no splash baffles were used. Splash baffles were not used because one set of runs with and without splash baffles indicated the same efficiencies within the limits of experimental error.

The pressure drop data range in this investigation from 0.4 to 1.8 in. of water are slightly lower than those predicted from correlations of Hughmark and O'Connell (*9*), which range from 1.1 to 2.1 in. of water. Probably the weeping encountered at low vapor rates reduced the liquid head on the plate and therefore the pressure drop. At the higher rates the experimental pressure drops and those predicted are much closer numerically.

An indication of the effect of each variable studied on efficiency as a function of vapor rate is given in Table 2. The change in efficiency shown is that caused by increasing the variable studied over the range indicated. In those cases, where the effect of one variable is influenced by changes in other variables, average values or ranges of values are given. It is interesting to note that plate spacing, hole diameter, free area, plate thickness, reflux ratio, and feed composition all have only a slight influence on efficiency over fairly wide ranges at moderate and high vapor rates. The variable hole spacing is not mentioned; it is considered a dependent function of free area, hole size, and effective plate area covered by perforations.

NOTATION

F_h = hole F factor defined as the product of the square root of the vapor density in lb./cu. ft. and the hole vapor velocity in ft./sec.

G = column superficial vapor mass velocity in lb./hr./sq. ft. of column superficial cross sectional area

L/D = external reflux ratio with the reflux rate divided by the distillate rate in moles/mole

n = number of theoretical stages required to accomplish a given separation

ΔP = single plate pressure drop in inches of water

P/D = hole pitch to diameter ratio defined as the smallest center to center distance between holes

x_b = mole fraction toluene in column bottoms product

x_d = mole fraction toluene in column distillate product

x = mole fraction toluene in the liquid phase

y = mole fraction toluene in the vapor phase

a = relative volatility defined as $y(1 - x)/x(1 - y)$, where y and x are equilibrium compositions

ρ = vapor density in lb./cu. ft.

Effective plate operation = general term designating characteristic area of plate operation where efficiency is near its maximum value and is not greatly changed by changes in vapor rate over a wide range

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