# Measured Plate Efficiencies and Values Predicted from Single-phase Studies

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**Plate efficiencies measured on 18-in.-diam. sieve plates are reported for the acetic acid–water system and for the methyl isobutyl ketone–water system at atmospheric pressure. In the former system the major resistance to mass transfer is in the gas phase; liquid-phase resistance to mass transfer is controlling in the latter. Efficiencies are also reported for the aniline-nitrobenzene system (gas-phase resistance controlling) at 5 mm. Hg absolute on 6-in.-diam. sieve plates. Pure gas- and liquid-phase efficiencies for both plate designs were determined by the adiabatic humidification of air and the desorption of oxygen from water into air. Predicted values of plate efficiency for each of the binary systems studied were computed from the pure phase efficiencies according to the procedure outlined by Gerster et al. A comparison between measured and predicted efficiencies is presented as a guide for future research in this field.**

The greatest uncertainty in the design of absorption and distillation columns today is in the conversion from theoretical to actual plates, that is, the problem of plate efficiency. This is true regardless of the type of contactor employed, whether bubble-cap plates, sieve plates, or some modification of these. Fortunately, however, this problem is recognized, and more and more work is being aimed at its solution. Perhaps the largest single effort in this endeavor is the A.I.Ch.E. research program on plate efficiency which is currently in progress at three universities.

Many methods for predicting mass-transfer efficiencies have been proposed (*2*, *5*, *6*, *15*). Some emphasize the importance of a certain variable or group of variables which are known to influence the final efficiency attained; others stress the importance of a different set of variables. None of these methods, however, take into account the variables concerned with changes in plate design, that is, the physical dimensions of the plate and its components.

A few years ago Gerster and others (*7*, *8*, *9*) proposed a method for predicting plate efficiencies by the addition of the separate gas- and liquid-phase resistances. This method takes into account all the factors now known to affect plate efficiency; furthermore, it permits allowances to be made for variations in plate design. Although Gerster's method is believed to be the best available, there actually has been very little confirmation of its accuracy and reliability in the literature, particularly for liquid-phase–controlled systems. Those applications which have been reported are confined to bubble-cap plates.

The authors have used this method with a reasonable degree of success for sieve plates, especially for systems in which the major resistance to mass transfer is in the gas phase. The purpose of this paper is to report some experiences with this method of predicting plate-efficiency values from single-phase studies. It is hoped that the results of this work will serve as somewhat of a guide for future research in this field. The experimental work reported herein covers three binary systems: acetic acid–water at atmospheric pressure, a gas-phase–controlled system; aniline-nitrobenzene at 5 mm. Hg absolute, another gas-phase-controlled system; and methyl isobutyl ketone–water at atmospheric pressure, a liquid-phase–controlled system. The atmospheric-pressure studies were made with 18-in.-diam. sieve plates; the vacuum study utilized 6-in.-diam. sieve plates.

## BACKGROUND

The Gerster method of predicting plate efficiency involves, first, determining the number of pure gas-phase transfer units $N_{Go}$ and the number of pure liquid-phase transfer units $N_{Lo}$ for a given plate, at the

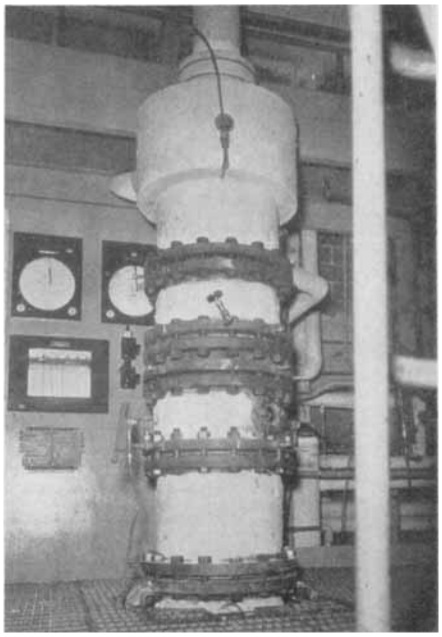

Fig. 1. Eighteen-inch-diameter stainless steel tower and control panel.

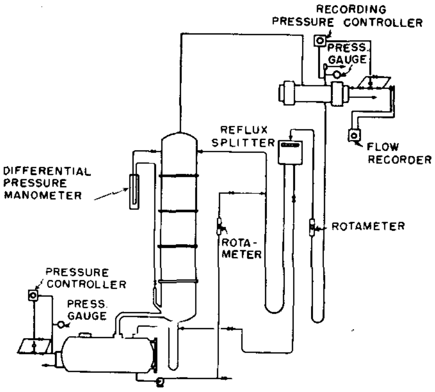

Fig. 2. Schematic arrangement of 18-in.-diam. stainless steel tower.

specified conditions of vapor and liquid flow, by the adiabatic humidification of air and the desorption of oxygen from water into air, respectively. These pure-phase transfer-unit values are then converted, by means of Schmidt-number ratios, to the individual transfer-unit values $N_G$ and $N_L$, which should exist on the given plate at the specified flow conditions with the system of interest. Equations (1) and (2) illustrate this conversion.

$$N_G = N_{G_o}\left(\frac{N_{Sc,G_o}}{N_{Sc,G}}\right)^{2/3} \tag{1}$$

$$N_L = N_{L_o}\left(\frac{N_{Sc,L_o}}{N_{Sc,L}}\right)^{1/2} \tag{2}$$

The gas- and liquid-phase Schmidt numbers are defined in Equations (3) and (4):

$$N_{Sc,G} = \frac{\mu_G}{\rho_G D_G} \tag{3}$$

$$N_{Sc,L} = \frac{\mu_L}{\rho_L D_L} \tag{4}$$

In this way the effect of physical properties, including viscosity, density, and molecular diffusivity, for both the liquid and the gas phases is recognized. The effect of variations in plate design on plate efficiency is accounted for in this method by determining values of $N_{G_o}$ and $N_{L_o}$ for the basic designs of interest. Finally, the converted transfer-unit values $N_G$ and $N_L$ are added together to yield an over-all transfer efficiency for the plate at the specific conditions, according to either Equation (5) or (6).

$$\frac{1}{-2.3 \log (1 - E_{OG})} = \frac{1}{N_G} + \frac{mG/L'}{N_L} \tag{5}$$

$$\frac{1}{-2.3 \log (1 - E_{OL})} = \frac{L'/mG}{N_G} + \frac{1}{N_L} \tag{6}$$

Equation (5) relates the individual transfer units $N_G$ and $N_L$, the vapor rate $G$, the liquid rate $L'$, and the slope of the equilibrium curve $m$ for the system of interest to the transfer efficiency of the plate $E_{OG}$, expressed as an over-all gas-phase efficiency. Equation (6) is the same type of relationship for the over-all liquid-phase efficiency $E_{OL}$. In Equation (5), the term $1/N_G + (mG/L')/N_L$ is a measure of the total resistance to mass transfer, $1/N_G$ representing the gas-phase resistance and $(mG/L')/N_L$ representing the liquid-phase resistance. Similarly, in Equation (6) $(L'/mG)/N_G$ represents the gas-phase resistance to mass transfer and $1/N_L$ represents the liquid-phase resistance. The values of $E_{OG}$ and $E_{OL}$ obtained in this manner are transfer efficiencies; the Lewis (*12*) equations must be used to obtain the corresponding Murphree values.

## APPARATUS

The work at atmospheric pressure, that is, the study of the acetic acid–water system and the methyl isobutyl ketone–water system, was carried out in an 18-in.-diam. stainless steel tower. This unit, shown in Figures 1 and 2, was designed to accommodate one to five plates at place spacings varying from 6 to 24 in. In this study, however, only three plates were employed. Plate spacing was altered by changing the order of the tower sections or by using special sections, depending on the spacing requirement. An 18-in. plate spacing was used with the acetic acid–water system and a 24-in. spacing with the methyl isobutyl ketone–water system. The tower was equipped with a shell-and-tube condenser, and the total condensate flowed from the condenser to a rotameter and then to a reflux splitter. The reflux leaving this splitter entered the tower just behind the inlet weir of the top plate. During the study of the methyl isobutyl ketone–water system additional reflux liquid was pumped from the boiling kettle, which was located directly beneath the tower, and joined the overhead reflux stream. The vapor from the kettle entered the side of the tower through a 6-in. pipe. The liquid overflow from the tower passed through a U-bend seal and returned to the top of the boiling kettle.

The 18-in.-diam. sieve plates (Figure 3) used in these studies had ⅛-in.-diam. holes on ⅜-in. equilateral triangular centers and provided a free area (total area of the holes) equal to 6.7% of the superficial tower area. The discharge weir height was adjusted to provide a minimum static seal of 1.5 in. for the acetic acid–water tests. A constant outlet weir height of 9/16 in. was used for all the methyl isobutyl ketone–water tests. Splash baffles were located ½ in. ahead of the discharge weir and their minimum clearance from the plate surface was ⅜ in. The tops of the splash baffles extended to within 3 to 4 in. of the plate above. These splash baffles were found necessary by actual experimentation. Without them the relatively small liquid flow across the plate in some of the runs was inadequate to maintain a constant seal depth.

For the measurement of the individual-phase efficiencies, one of the 18-in.-diam. plates was set up in a special apparatus designed to accommodate only one test plate. In order to procure reliable data from adiabatic humidification and oxygen desorption, the tests should be carried out across one plate only. If more than one plate is used, the approach to equilibrium conditions is so close that the resulting calculated individual-phase efficiencies have low precision.

The work at 5 mm. Hg abs., that is, the study of the aniline-nitrobenzene system, was carried out in a 6-in.-diam. stainless steel column. This unit was simply a 10-ft. section of 6-in. pipe without intermediate-section flanges. Since this unit was designed for high-vacuum studies down to 1 mm. Hg absolute, flanges and connections were kept at a minimum. The plates (Figure 4) were slipped into the column and spaced on 12-in. centers by three support posts between each plate. The plates were sealed to the column with an 0-ring–packing arrangement. This tower was also equipped with a shell-and-tube condenser, and the total condensate flowed from the condenser, through a gas-disengaging chamber to allow inerts to go to the jets, to a rotameter, and then to the top of the column behind the inlet weir on the top plate. Vacuum was supplied by a four-stage jet arrangement, and the desired absolute pressure was maintained by a controlled air bleed.

Six 6-in.-diam. sieve plates on 12-in. plate spacing were used in the study of the aniline-nitrobenzene system. These plates also had ⅛-in. holes on ⅜-in. equilateral triangular centers. The free area (total area of the holes) for the 6-in.-diam. plates was 5% of the superficial tower area. The

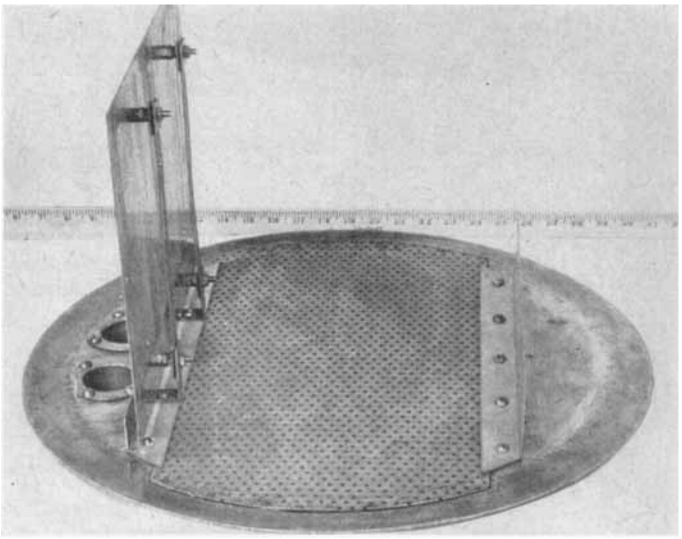

**Fig. 3. Sieve plate tested in the 18-in.–diam. tower.**

circular discharge downpipe on each plate was adjusted to provide a minimum static seal of ¾ in. Splash baffles in the form of tubes concentric with the downpipes and slotted at the base for the passage of liquid were found to be necessary to maintain a constant seal on the plates.

One of these plates was set up in a 6-in.-diam. Lucite acrylic-resin tower for the measurement of the individual-phase efficiencies. Here again, a single plate was found necessary, particularly for the region of low liquid rates encountered in vacuum distillation.

## BASIC DATA

The vapor-liquid equilibrium data for the acetic acid–water system at atmospheric pressure which were used in the calculation of the actual efficiencies represent an average of those found in the literature supplemented by data obtained from unpublished information. These data are shown in Table 1 for the concentration range covered in this study.

TABLE 1
VAPOR-LIQUID–EQUILIBRIUM DATA FOR WATER AND ACETIC ACID

| Mole fraction of water in Liquid | Vapor |
|---|---|
| 0.9200 | 0.9424 |
| 0.9300 | 0.9493 |
| 0.9400 | 0.95635 |
| 0.9500 | 0.9636 |
| 0.9600 | 0.97085 |
| 0.9700 | 0.9782 |
| 0.9800 | 0.98545 |
| 0.9900 | 0.9927 |
| 1.0000 | 1.0000 |

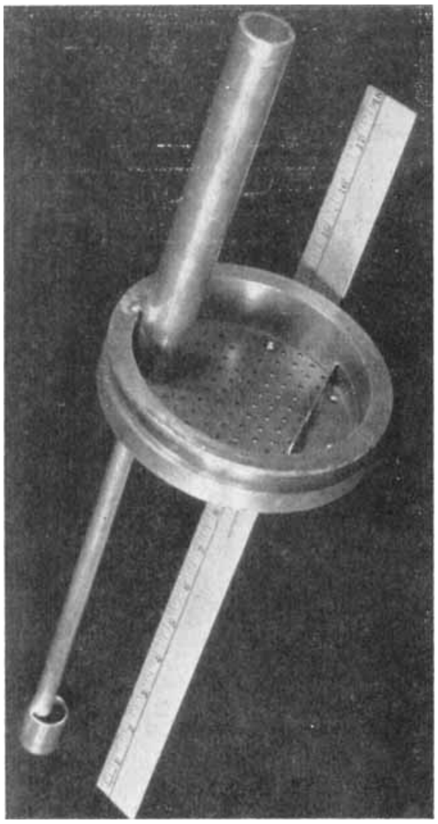

**Fig. 4. Sieve plate tested in the 6-in.-diam. tower.**

TABLE 2
SCHMIDT NUMBERS USED IN PLATE-EFFICIENCY PREDICTIONS

| System | $N_{Sc,G}$ | $N_{Sc,L}$ | Temperature, °C. |
|---|---|---|---|
| Oxygen-water | — | 344 | 25 |
| Air-water vapor | 0.60 | — | 25 |
| Water-acetic acid | 1.12 | 82.7 | 100 |
| Aniline-nitrobenzene | 0.47 | 1,050 | 56 |
| Methyl isobutyl ketone–water | 1.65 | 90.2 | 100 |

Vapor-liquid equilibrium data for the methyl isobutyl ketone–water system were computed, according to equations in Perry (*13*), from solubility data measured at 20°, 40°, 60°, 80°, and 87.5°C. and from measured vapor-pressure values. In the dilute methyl isobutyl ketone concentration range, the region used in this experiment, the slope of the equilibrium curve $m$ is essentially constant at 200. Hence, this constant value was used throughout in all efficiency calculations.

Vapor-liquid equilibrium data for the aniline-nitrobenzene system at 5 and 10 mm. Hg absolute were calculated from total-pressure measurements of mixtures of these two compounds and from vapor-pressure measurement of the pure components according to a method outlined by Holtzlander and Riggle (*10*). These data are shown in Figures 5 and 6.

## TEST PROCEDURE

For all the runs made in this investigation with the acetic acid–water system the tower was operated at atmospheric pressure and total reflux. At the beginning of each run the boil-up was adjusted to the desired rate as indicated by the condensate rotameter. This established rotameter reading was held within ±5% for an hour to ensure equilibrium before sampling procedures were started. When any significant fluctuations in the boil-up rate occurred during the waiting period, the column was brought back to the desired rate and a full hour was allowed to elapse before sampling. This period ensured a minimum of four complete changes of holdup at the desired vapor rate.

The runs with the methyl isobutyl ketone–water system were also made at atmospheric pressure, but liquid-to-vapor ratios in the range of 1:1 to 40:1 were studied. After the boil-up had leveled off at total reflux, the pump which recirculated liquid from the boiler to the reflux inlet was started and the flow was adjusted to the desired reading on a rotameter. After steady operation had been attained, approximately 1 hr. elapsed before liquid samples for efficiency determinations were taken.

The boil-up rates for all tests in the 18-in.-diam. tower were computed from recorded inlet and outlet condenser cooling-water temperatures and a direct weighing measurement of the cooling-water rate. The steam condensate from the reboiler was measured as an additional check. The temperatures of the reflux, condensate, and boiling kettle were also recorded. The differential pressure drop across the three plates was measured by a water manometer. All recorded data were taken in duplicate, one set immediately preceding the efficiency samples and one set following. With the methyl isobutyl ketone–water system, two sets of liquid samples were taken about 1 hr. apart to ensure that steady state conditions prevailed.

Only liquid samples were taken for the efficiency determinations. Since the overhead vapor was totally condensed, a sample was taken from the reflux line to determine the composition of the liquid entering the top plate, which for the ketone–water runs was a composite of the totally condensed overhead vapor and the liquid reflux being pumped from the reboiler. A second sample, taken from the U leg leading back to the reboiler, determined the composition of liquid leaving the bottom of the tower. All samples from the 18-in.-diam. column were taken through chilled copper coils to prevent flashing. The sampling connection and line were thoroughly flushed before the sample was taken.

The procedure followed with the aniline-nitrobenzene system in the 6-in.-diam.

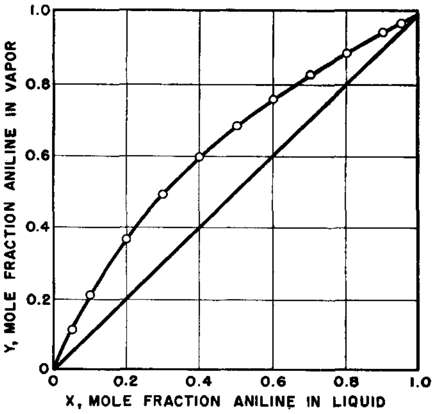

**Fig. 5. Vapor-liquid–equilibrium data for aniline nitrobenzene at 5 mm. Hg abs.**

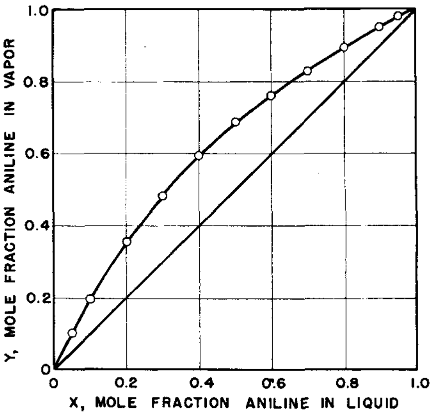

**Fig. 6. Vapor-liquid–equilibrium data for aniline nitrobenzene at 10 mm. Hg abs.**

column at 5 mm. Hg abs. was similar to that for acetic acid–water. In the vacuum studies, however, the desired top-column pressure was established and under control before heat was applied to the reboiler. Temperatures were measured in the reboiler, bottom column, top column, overhead vapor line, and condensate line. Boil-up was determined by a calibrated rotameter in the overhead condensate line. The differential pressure drop across the six plates was measured by a dibutyl phthalate manometer. Liquid samples for efficiency determination were taken from the overhead condensate line and from the U leg leading back to the reboiler.

As stated above, the adiabatic-humidification tests and the oxygen-desorption tests had to be carried out across one plate only. The oxygen-desorption runs were made by dissolving oxygen in water and pumping the solution to a calming section. Calming sections extended 2 ft. from either side, upstream and downstream, of the test section which held the 18-in.-diam. test plate. The calming sections allowed a reasonably accurate measure of the clear liquid head at each end of the unit and provided a good sample of liquid. With a blank plate in place, oxygenated water was passed through the unit in order to measure the extent to which oxygen was lost from the water in the calming sections. The loss of oxygen was found to be negligible. Samples taken at the center line and near the side wall of the calming sections showed that the liquid composition was uniform across the channel. In the case of the 6-in.-diam. plates no calming section was used; the liquid entered the plate behind an inlet weir, flowed across the plate, under the splash baffle, and over into the cylindrical downpipe. The air and water temperatures were controlled in all runs so that the wet-bulb temperature of the entering air was at the inlet-water temperature to ensure a constant water temperature across the plate and thus no change in the oxygen solubility.

Adiabatic-humidification runs were made in the same way as the oxygen-desorption runs, except that the inlet and exit dry- and wet-bulb temperatures of the air were noted for each test condition. In all cases the water and air temperatures were set so that the wet-bulb temperature of the air was at the temperature of the water. The dry-bulb temperature of the exit air was measured sufficiently far downstream so that there was no appreciable liquid entrainment to the thermometer; furthermore, the wet- and dry-bulb thermometers were located behind a baffle in the outlet duct.

## ANALYTICAL PROCEDURE

The acetic acid–water samples used to determine plate efficiency were titrated to a phenolphthalein end point with 0.1$N$ sodium hydroxide solution. Results of the titration were converted to mole fractions of water.

The aniline-nitrobenzene samples were analyzed for aniline by titration with 0.1$N$ perchloric acid in a glacial acetic acid medium. Crystal violet dissolved in glacial acetic acid was the indicator. The results of these titrations were converted to mole-fraction units.

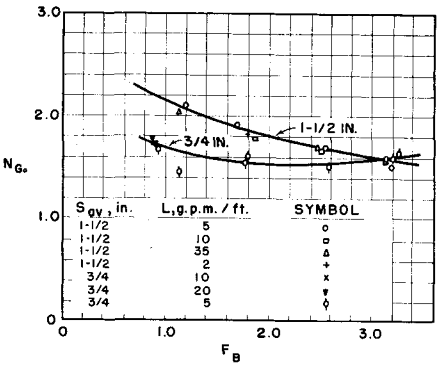

**Fig. 7. Number of gas-phase transfer units for 18-in.–diam. sieve plate.**

The methyl isobutyl ketone–water samples were analyzed for the ketone by means of the iodoform reaction. An excess of iodine added to a weighed sample formed a precipitate with the ketone, and the unreacted iodine was titrated with 0.1$N$ sodium thiosulfate solution to a starch-solution end point. Analyses were computed in mole-fraction units. Oxygen analysis was made by the Winkler method.

## EFFICIENCY CALCULATIONS

The average actual plate efficiency for the three plates operating at total reflux on the acetic acid–water system was calculated according to the method of Baker and Stockhardt (*1*). This procedure involves the assumption that Murphree efficiency does not vary from one plate to the next and that only two liquid samples are required: condensate and run-off from the bottom plate. The concentrations of these two samples were plotted on a McCabe-Thiele diagram, and the efficiency was determined by trial and error. Three fractional plates were stepped off by means of proportional dividers, the plate efficiency fraction being changed on each successive trial until the fraction was found which gave the experimentally determined separation in three steps. This fraction then represented the average Murphree vapor efficiency $E_{MV}$ of the three plates.

The average actual plate efficiency for the three 18-in.-diam. plates operating at various reflux ratios on the methyl isobutyl ketone–water system was determined analytically by means of Silver's (*14*) modifications of Colburn's (*4*) equations, which are valid for cases in which the operating and equilibrium lines are straight. Efficiency values for this system were computed as $E_{MV}$, Murphree vapor efficiency.

For the aniline-nitrobenzene system, a plot was made of theoretical plates vs. composition, with a very low concentration of aniline (0.0001 mole fraction) used as a base point. The theoretical plate value corresponding to the aniline concentration in the liquid leaving the bottom plate of the column was subtracted from the theoretical plate value corresponding to the aniline concentration in the liquid reflux to the top plate of the column. This gave the total number of theoretical plates achieved across the six actual plates, and the ratio of theoretical plates to actual plates was taken as the average plate efficiency. Actually an efficiency calculated in this manner may not be the same numerically as a Murphree vapor efficiency. Several runs, covering the complete range of the experiments, were also reevaluated by means of the Baker and Stockhardt (*1*) method as used on the acetic acid–water system. In the case of the aniline-nitrobenzene system, the maximum deviation between efficiencies computed by these two methods was 1 to 3%. The use of over-all plate efficiencies, as the ratio of theoretical to actual plates, is not recommended for column design unless some check with the Baker and Stockhardt (*1*) method is made.

## RESULTS

Data on the number of pure-gas-phase transfer units on the 18-in.-diam. plate are shown in Figure 7 as $N_{G_o}$ vs. the

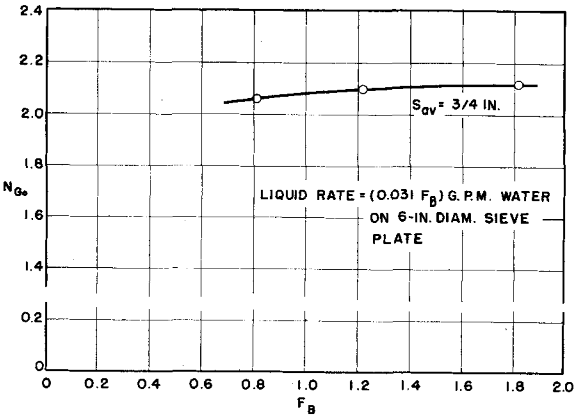

**Fig. 8. Number of gas-phase transfer units for 6-in.–diam. sieve plate.**

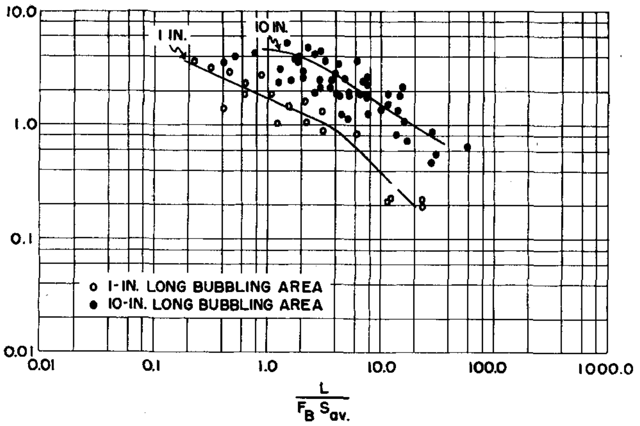

**Fig. 9. Number of liquid-phase transfer units as measured on 18-in.-diam. sieve plate.**

$F$ factor in the bubbling area $F_B$, with average clear-liquid-seal depth $S_{avg}$ as a parameter. The average clear-liquid-seal depth for the single 18-in.-diam. test plate was taken as the arithmetic average of the clear liquid depths in the upstream and downstream calming sections, measured directly as clear-liquid depths. In the case of the 18-in.-diam. plates in the column, where no calming sections could be used, the average clear-liquid-seal depth was calculated as the height of the outlet weir plus the computed crest of clear liquid over the weir plus one-half the hydraulic gradient across the plate. (Hydraulic gradient across plates of this diameter at the liquid rates employed in these tests is usually negligible.) It is assumed that liquid flows over the outlet weir as a clear liquid, as a splash baffle was used on all plates in the columns. For the 6-in.-diam. plates, where no calming sections could be used either, the seal was adjusted to give the same pressure-drop curve as measured with an $S_{avg}$ of $\frac{3}{4}$ in. on the single 18-in.-diam. test plate with calming sections. The $F$ factor is defined as the product of the linear vapor velocity, expressed in feet per second and based upon the total cross-sectional area of the column and the square root of the vapor density, the density being expressed as pounds per cubic foot. $F_B$, the $F$ factor in the bubbling area, is based upon the cross-sectional area of the bubbling zone. The bubbling area on the 18-in.-diam. plates was about 62.5% of the total cross-sectional area of the column; on the 6-in.-diam. plates, the bubbling area was about 54% of the total column area. It is interesting to note that the curve for either seal depth is made up from data taken at several different liquid rates. This indicates that the number of gas-phase transfer units is independent of liquid rate $L$, expressed as gallons per minute per foot of plate width. The number of gas-phase transfer units is also practically independent of $F_B$, a direct measure of the vapor rate.

The same type of data were measured on the 6-in.-diam. sieve plates at a nominal seal of $\frac{3}{4}$ in. and they are shown on Figure 8. The difference in the number of gas-phase transfer units for the 18- and the 6-in.-diam. plates at the same average seal of $\frac{3}{4}$ in. is undoubtedly the result of discrepancies in the measurement of the clear-liquid seal on these plates. As explained above, calming sections were used with the 18-in.-diam. test plate but not with the 6-in.-diam. test plate.

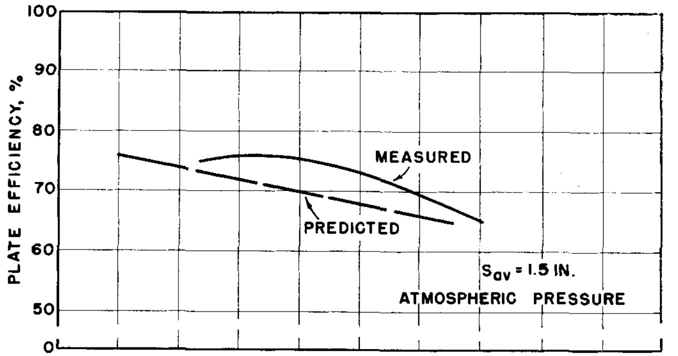

Fig. 10. Comparison of measured and predicted plate efficiencies; 18-in.-diam. column, acetic acid–water system.

Data on the number of pure liquid-phase transfer units on the 18-in.-diam. plates used in these tests are shown in Figure 9 as $N_{L_o}$ vs. a term $L/(F_B S_{avg})$. For this correlation, it was assumed that the interfacial area for mass transfer is directly proportional to $F_B$, the $F$ factor in the bubbling area, and that the liquid-phase mass transfer coefficient, usually indicated as $k_L a$, is constant across the plate. The liquid-phase transfer units are shown for a 10-in. length of liquid path, which was the dimension of the perforated section in the direction of net liquid flow. When similar measurements were made on the 6-in.-diam. plate, it was found that the oxygen content of the water was reduced to the equilibrium value (within the precision of analysis) for all conditions. The length of liquid path on the 6-in.-diam. plates was 3 in. Since the 6-in.-diam. plates were being used for vacuum studies, the liquid reflux rates were quite small. According to the theory and basic assumptions made in the development of the Gerster approach, the number of liquid-film transfer units on a plate is proportional to the length of liquid path. Hence all but a 1-in. length of perforations on the 18-in.-diam. plate were blanked off, and the oxygen-desorption tests were repeated with the results as shown. These values of the number of liquid-phase transfer units for a 1-in. length of liquid path, multiplied by 10 in the case of the 18-in.-diam. plates and by 3 in the case of the 6-in.-diam. plates, were used in all efficiency predictions.

Values in Figures 7, 8, and 9 were used at the appropriate gas rate, liquid rate, and seal depth, along with Equations (1), (2), and (5) to predict values of $E_{OG}$, the transfer efficiency based upon over-all gas-film driving force for each of the systems studied. The calculated values of the Schmidt numbers which were used for the conversions indicated in Equations (1) and (2) are given in Table 2.

The comparison between predicted and measured plate efficiency values for the acetic acid–water system at atmospheric pressure and total reflux is shown in Figure 10. This system is predominantly gas-phase controlled, with more than 90% of the total resistance in the gas phase at the conditions studied. The agreement between predicted and measured plate efficiency over the entire range studied is seen to be very good. The maximum difference is about 3%. Since the plate spacing was 18 in., some correction for entrainment effects might be applied to the predicted values at the higher vapor rates.

For the aniline-nitrobenzene system at 5 mm. Hg abs. and total reflux, the same comparison is made in Figure 11. Since only a 12-in. spacing separated the plates during the vacuum tests, corrections for entrainment effects on the predicted efficiency were made according to the equation derived by Colburn (*3*). Entrainment values were estimated from data measured and reported by Jones and Pyle (*11*). In this system approximately 75% of the resistance to mass transfer occurs in the gas phase at the conditions maintained in our tests. Here again the agreement between predicted and measured plate efficiency is quite good. In this case adiabatic-humidification data and oxygen-desorption data, both measured at atmospheric pressure, were used, together with physical-property data, to predict plate efficiencies for the aniline-nitrobenzene system at 5 mm. Hg abs.

The comparison between predicted and measured efficiencies for the methyl isobutyl ketone–water system at atmospheric pressure and at varying reflux ratios is shown in Figure 12. In this system 70 to 80% of the total resistance to mass transfer is in the liquid phase for the operating conditions which were maintained during these tests. The upper curves are for an average seal depth of 1.3 to 1.4 in. of clear liquid, and the lower curves are for an average clear-liquid-seal depth of 0.9 to 1.0 in.

At the higher seal the liquid rate $L$ was approximately 25 (gal./min.)(ft.) of plate width, and the liquid-to-vapor reflux ratio $L'/G$ varied from about 40:1 at the low vapor rate to about 8:1 at the high vapor rate. At the higher seal fairly good agreement exists between the predicted and measured efficiency values at the lower vapor rates. As the vapor rate increases, the difference between predicted and measured efficiency widens as a result of a substantial drop in the measured values.

At the lower seal the liquid rate $L$ was approximately 10 (gal./min.)(ft.) of plate width, and the liquid-to-vapor reflux ratio $L'/G$ varied from about 10:1 to about 3:1. At the lower liquid rate and low vapor rates, measured efficiencies are somewhat higher than the predicted values. As the vapor rate increases, this situation reverses and the predicted values are much greater than the measured ones. Since a 24-in. plate spacing was used in the ketone-water tests, very little of the difference between the predicted and measured values can be attributed to entrainment effects, even at the higher vapor rates.

The experimental data which form the basis of the measured plate-efficiency curve in Figure 10 are taken from Table 1 of Jones and Pyle (*11*). The experimental data for the measured efficiency curves in Figures 11 and 12, respectively, are contained in Tables 3 and 4* of this paper. These tabulations include temperatures, pressure, pressure drop, sample compositions, boil-up rate, $F$ factor, reflux ratio, and plate efficiency.

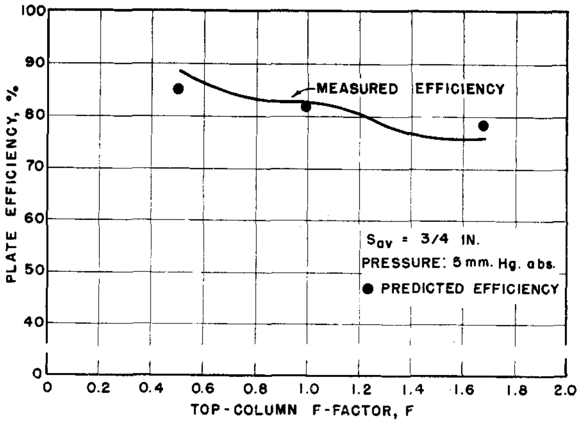

**Fig. 11. Comparison of measured and predicted plate efficiencies; 6-in.-diam. column, aniline-nitrobenzene system.**

DISCUSSION OF RESULTS

It is to be noted that in all the results a comparison is made between a predicted transfer efficiency and a measured Murphree efficiency, or its equivalent in the case of the aniline-nitrobenzine system.

Early in this work it became apparent that mixing of the liquid in the direction of net liquid flow was taking place on the sieve plates. It was found that the number of liquid-phase transfer units calculated from the oxygen-desorption tests was not directly proportional to length, as theory would predict. It can be seen from Figure 9 that the number of liquid-phase transfer units for a 10-in. liquid path is not ten times the number of liquid-phase transfer units measured for a 1-in. liquid path. This deviation from theory is attributed to liquid mixing in the direction of net liquid flow. Such mixing would be expected to be more pronounced at low liquid flows and high vapor rates. This variation in the number of liquid-phase transfer units per unit of length

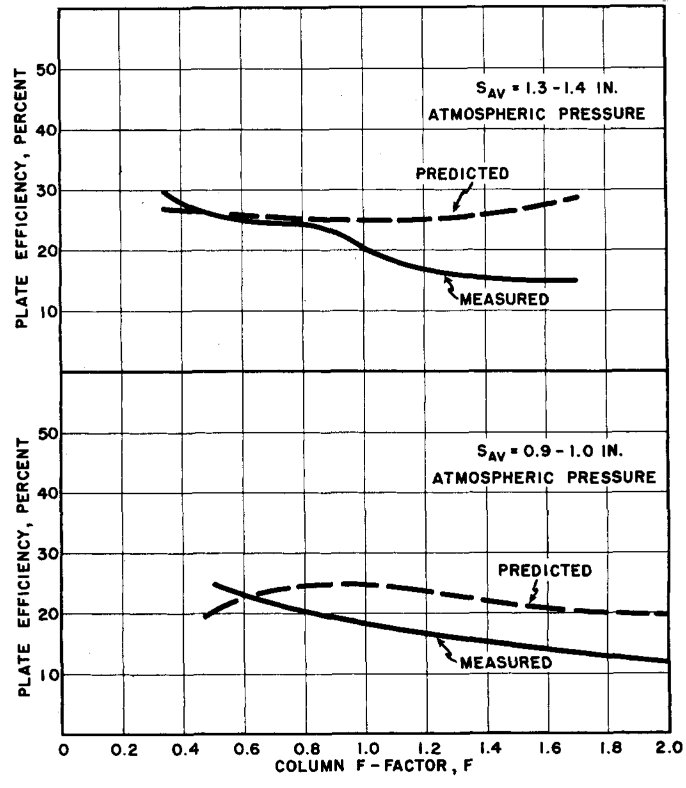

**Fig. 12. Comparison of measured and predicted plate efficiencies; 18-in.-diam. column, methyl isobutyl ketone–water system.**

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*Tabular material has been deposited as document 5310 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.

with length does *not* seem to be particularly serious for systems with high gas-phase resistance. In the case of the acetic acid–water system the predicted $E_{OG}$ would have been about 2% lower if calculated from the 10-in. curve rather than the 1-in. curve. In the case of liquid-phase–controlled systems, however, this difference can be quite large. For the methyl isobutyl ketone–water system at $S_{avg}$ of 1.3 to 1.4 in. the predicted transfer efficiencies $E_{OG}$ calculated from the 1-in. oxygen-desorption data are about 25% (Figure 12). When calculated from the 10-in. oxygen data, the predicted transfer efficiencies become 12 to 15%. At the lower seal, $S_{avg}$ of 0.9 to 1.0 in., the predicted efficiencies based upon the 1-in. oxygen data are 20 to 25% but only 8 to 10% based upon the 10-in. oxygen data.

It was found that the predicted transfer efficiencies $E_{OG}$ for the acetic acid–water system, as calculated from the 1-in. oxygen data, agreed quite well with the measured Murphree efficiencies $E_{MV}$ (Figure 10). If the predicted transfer efficiencies had been corrected for cross flow by the Lewis (*12*) equations, with no liquid mixing assumed in the direction of net liquid flow, the resulting predicted Murphree efficiency curve would have been about 15% higher than the measured curve. Hence, it was concluded that a great amount of liquid mixing did occur during the acetic acid–water tests. For this reason, the procedure of calculating sieve-plate transfer efficiencies based upon the 1-in.-long experimental plate with no correction made for cross-flow effects was adopted. All the predicted efficiencies shown in Figures 10, 11, and 12 were computed in this manner.

This procedure has been quite satisfactory for gas-phase–controlled systems (Figures 10 and 11). On larger diameter plates, where liquid mixing might be less than on the smaller plates, such a procedure should give conservative values for predicted plate efficiencies. In the case of a liquid-phase–controlled system, however, this procedure gives predicted plate efficiencies higher than measured. Hence at the present time it should be used only as a rough estimate of plate efficiency for liquid-phase–controlled systems.

As mentioned before, the Gerster approach takes into account all the factors now known to affect plate efficiency, including variations in plate design. When this approach was first presented, it appeared that after the effects of operating and design variables on the individual-phase efficiencies were determined on small-scale plates, it would then be possible to predict from such data efficiencies for any system on any size plate. Although the Gerster approach may still basically have such a potentiality, its utility is somewhat limited, for the present at least, because no quantitative value has been placed on the effect of the various degrees of liquid mixing which are encountered. On large-diameter plates operating with low vapor rates and high liquid rates, liquid mixing in the direction of net liquid flow is expected to be at a minimum, but on small plates operating with high vapor rates and low liquid rates, liquid mixing will be essentially complete. The former situation is handled by the Lewis (*12*) equations; in the latter situation the Murphree efficiency and the transfer efficiency are identical. The vast majority of cases of interest, however, will be somewhere between these two extremes.

Actually, mixing of liquid probably does not change the true efficiency of the plate. It does, however, reduce the total separation achieved across a plate because a reduction in the total driving force for mass transfer results from the mixing. It now appears that some quantitative definition of mixing, expressed as a function of plate design and operating variables, will have to be developed and related to concentration gradients on an an active plate before plate-efficiency predictions can be made with confidence for both gas- and liquid-phase–controlled systems from single-phase studies.

## SUMMARY

Murphree vapor efficiencies have been measured on 18-in.-diam. sieve plates for the acetic acid–water system and for the methyl isobutyl ketone–water system at atmospheric pressure. In the former system the major resistance to mass transfer is in the gas phase; liquid-phase resistance to mass transfer is controlling in the latter. Murphree vapor efficiencies have also been determined for the aniline-nitrobenzene system, gas-phase resistance controlling, at 5 mm. Hg abs. on 6-in.-diam. sieve plates. Predicted values of over-all gas-phase transfer efficiency for each of these binary systems have been computed from pure-phase efficiencies according to the method suggested by Gerster et al. (*7*, *8*, *9*). A comparison between predicted and measured values shows good agreement for those cases in which the major resistance to mass transfer is in the gas phase. In the case of liquid-phase–controlled systems it is recommended that for the present this method be used only for obtaining a rough estimate of the actual plate efficiency. It is suggested that an unknown amount of liquid mixing in the direction of net liquid flow is the main factor contributing to the discrepancy between predicted and measured plate-efficiency values for liquid-phase–controlled systems. Further research on the mixing phenomena will be required before plate-efficiency predictions can be made with confidence for both gas- and liquid-phase–controlled systems from single-phase studies.

## NOTATION

$D$ = molecular diffusivity, sq. ft./hr.
$E_{MV}$ = Murphree plate efficiency, over-all gas-concentration basis
$E_{ML}$ = Murphree plate efficiency, over-all liquid-concentration basis
$E_{OG}$ = transfer efficiency, over-all gas-concentration basis
$E_{OL}$ = transfer efficiency, over-all liquid-concentration basis
$F$ = $F$ factor based on tower cross-section area, $F = v\sqrt{\rho_G}$
$F_B$ = $F$ factor based on bubbling area
$G$ = gas mass velocity, lb. moles/(hr.)(sq. ft. of tower cross-sectional area)
$L$ = liquid rate, (gal./min.)(ft. of plate width)
$L'$ = liquid mass velocity, lb. moles/(hr.)(sq. ft. of tower cross-sectional area)
$m$ = slope of equilibrium curve
$N_G$ = number of gas-phase transfer units
$N_L$ = number of liquid-phase transfer units
$N_{Sc}$ = Schmidt number, $\mu/\rho D$
$S_{avg}$ = average seal depth, in. of clear liquid
$v$ = superficial linear vapor velocity, ft./sec.
$x$ = mole fraction of designated component in liquid
$y$ = mole fraction of designated component in vapor
$\mu$ = viscosity, lb./(ft.)(hr.)
$\rho$ = density, lb./cu. ft.

### Subscripts

$L$ = liquid
$G$ = vapor
$o$ = pure-phase measurements

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