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Studies on Distillation: XX.* Efficiency of Selected Types of Large Distillation Trays at Total Reflux

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Summary

Using improved methods of vapor and liquid sampling of the streams around a distillation tray, it was possible to obtain accurate values of the compositions of all these streams. These data enabled us to calculate the liquid weeping and carryover from the tray, where the latter data agree reasonably with published correlations and to determine plate efficiencies in the presence of such entrainment streams. Three tray efficiencies are considered: the apparent, based on the actual stream concentrations; the reduced, based on the use of reduced concentrations introduced recently; and the conventional, based on an incorrect, but generally employed, procedure. The data were obtained on a large research distillation column by testing bubble-cap, sieve, Uniflux, APV-West, Ripple, and Turbogrid trays. The conventional efficiencies are also compared with published correlations, usually with fair agreement.

As part of our general research program of studying the operating characteristics of distillation trays, we measured the plate efficiencies of a set of common types of trays on a large research column to provide a basis of comparison with Turbogrid trays, which were the main interest of our studies. The results of this work are reported in this paper.

As we wished to take account of the possible effect of liquid

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carryover or weeping on plate efficiency discussed theoretically earlier (*1*,*2*), we devoted special attention to the question of obtaining representative samples of the vapor as well as liquid streams flowing from plate to plate along the column, to be able both to determine directly the entrainment itself and to obtain plate efficiencies which take it into account in a manner consistent with the material balances.

STREAM SAMPLING

As soon as we give up the naive conception of a theoretical plate presented in elementary textbooks, we find that there is a whole complex of questions which must be considered when we wish accurately and realistically to describe the behavior of actual trays even as far as concerns the mass transfers occurring on them or the influence of tray hydrodynamics on these transfers. These problems also find their reflection in questions concerning the experimental determination of plate efficiencies from the concentrations of samples of the streams entering and leaving the plate. The use of material balances describing quantitatively the changes in the average concentrations of the streams from plate to plate is basic to the analysis of these mass transfers and plate efficiencies.

First, it is an almost universal practice to assume steady-state conditions in the column when considering plate efficiencies, as is reasonable since most industrial columns operate at or near steady state. On the experimental side, since we cannot assume that there will not be turbulent concentration fluctuations in a stream at a given point (and, in fact, they undoubtedly occur), we must take stream samples in such a way as to obtain proper time-average values. This requirement is usually met without special measures being required, as stream samples are usually withdrawn from the column slowly over a period of 10–20 min, which is much longer then the periods of the concentration fluctuations. (The corresponding problem of measuring time-average stream temperatures is much more difficult.)

More serious is the problem of obtaining representative cross-section averaged samples of the streams. On cross-flow trays with downcomers we have, in general, horizontal concentration gradients in the liquid in the direction of liquid flow and hence in the vapor leaving the tray. We have, however, no assurance that there will not also be horizontal gradients in the perpendicular direction due to flow nonuniformities. Similarily, with trays without downcomers, it is not possible, in reality, to assume completely uniform flow and hence a complete absence of horizontal concentration gradients over the plate. All these nonuniformities are important as the plate material balances and efficiencies are expressed in terms of cross-section averaged stream concentrations. When specifying the cross sections of the column defining the limits of a single plate and hence the average stream concentrations, it is desirable to choose these sections so that the concentration nonuniformities will be as small as possible, both so that the plate-to-plate theoretical calculations will correspond as closely as possible to reality and also so that the sampling difficulties will be as small as possible. Thus with trays with downcomers, it is desirable to take the liquid outlet cross section near the bottom of the downcomer to give maximum opportunity for liquid cross-mixing before the section is reached; in general, the vapor-outlet cross section should be as far as possible from the given plate (i.e., as near the next plate above), for the same reason. Where these measures do not suffice, it is therefore desirable to have more than one sampling probe or, better, a traveling probe over the cross section. Even when this is done, the proof that properly representative samples have actually been obtained for use in material balances, and especially plate efficiencies, where we are dealing with the ratio of two small changes in stream concentrations, is often inadequate. Indeed, the exact cross sections of the column chosen for defining the states of the streams occurring in the material balances and plate efficiencies are often not sufficiently clearly specified.

Although concentration gradients across the stream cross sections are not necessarily detrimental to the functioning of the column as a separating device (indeed, if properly utilized, they may enhance it), certain other effects which have been too often neglected always are. A plate is actually a repeating segment of a column where the entering nonequilibrium vapor (light phase) and liquid (heavy phase) are intensively mixed by dispersion so that mass and heat (energy) transfer can occur between the contacting phases. After contact the phases are to be separated for further contacting or treatment.

One difficulty is that the intense mixing of the phases in the dispersed foam on the plate leads to sharp concentration changes in the streams at their entrance to the foam and hence to axial transfer along the direction of flow of the entering stream at these points. Axial mixing is, in general, detrimental to efficient separation, and it is good practice in plate designs to limit its effects to the minimum, e.g., by installing an inlet weir just beyond the exit from a downcomer. From our point of view it is important not to locate a sampling probe in a region with significant axial mixing, as it is difficult to correct for the concentration shifts caused by it. In practice this requirement means that, although we should locate the vapor samplers as far from the given plate as possible, they should not be too near the vapor inlets to the upper tray, and in trays with downcomers the liquid samplers, if located near the bottom of the downcomers, should not be too close to the liquid inlet to the lower plate; usually a few centimeters separation is sufficient. It should be noted that, according to the Danckwerts' boundary conditions (3), no such effects due to axial mixing occur at the exits from a plate.

Far more serious is the correct interpretation of material balances and plate efficiencies in the presence of stream carryovers, weeping, dumping, etc., which always decrease the separating ability of the column, so that it is important to choose the design of the tray so as to minimize these entrainments. Even so, while here the correct choice of the column cross section corresponding to maximim separation of the phases and minimum entrainment is also important, for reasons analogous to those given above for lateral mixing, it is not possible in many cases corresponding to industrial practice to solve the problem by proper tray design and then suitable choice of column cross sections, because even with the best choice the amount of entrainment often remains significant, usually because of the deliberately chosen high loading of the column, and it should therefore be taken into account both in plate-to-plate calculations (2) and in plate-efficiency determinations. So far, however, this has not been done in a systematic and consistent manner.

In principle we can withdraw a "wet" sample of the given stream together with the entrained stream (or streams) or a "dry" sample without it. Practically, however, it is almost impossible to withdraw a wet sample of the stream while ensuring that the entrained stream is sampled in the same state and relative amount, as in the column cross section. Thus we must make the second choice and ensure that the sample probe withdraw only a dry sample of the given stream and completely eliminate the entrained stream present at that point in the column. Furthermore, during this elimination (or subsequently) no change in the composition of the sampled stream may occur if we are to obtain true values of the concentrations by subsequent analysis.

Obtaining representative liquid samples is simpler than in the vapor case for several reasons. First, the large difference in vapor and liquid densities means that a given relative volumetric entrainment of vapor in the liquid sample has an effect on the composition of the final condensed sample several orders of magnitude smaller than an equal relative volumetric entrainment of liquid in the vapor sample. In fact, a small relative volumetric entrainment of vapor in the liquid sample hardly affects the resultant composition, whereas we obtain a representative final sample of condensed vapor only if even small relative volumetric liquid entrainments in the vapor sample are rigorously excluded. Second, again thanks mainly to the differences in densities, the largest liquid drop entrained by the vapor stream is usually substantially larger than the largest vapor bubble entrained by the liquid stream in the column cross section. In distillation columns we can therefore usually find suitable column cross sections where the entrainment of vapor by liquid is negligible—in trays with downcomers, at the bottom of the downcomer, and in trays without downcomers, just below the liquid exits from the tray—as is easily confirmed by observation on hydraulic models (*4*), where it can be seen that the liquid at these points is clear. Just the opposite is true for the vapor stream at high column loadings where we often still have significant liquid carryover even at the vapor exit to the next higher plate. Thus in distillation (and absorption), by a suitable choice of cross sections, we can practically eliminate vapor entrainment by liquid streams, but not, in general, liquid entrainment by vapor streams. (Analogous conclusions do not apply to extraction, where as a rule we encounter both types of entrainment.) Furthermore, the vapor at the sampling point, in general, is not, in either concentration or temperature equilibrium with the liquid, carried over from the lower plate, and even less with any liquid which may be weeping or draining from the higher plate. Thus the sampling probe must withdraw a dry vapor sample while preventing any additional heat or mass transfer between the phases. The situation is especially difficult with trays without downcomers, where the sampler must work in a "rain" of the entire colder and richer liquid from the higher plate and not of just the relatively small weep flow (if any is present) as with trays with downcomers, in addition, of course, to the liquid carryover from the plate below.

EXPERIMENTAL PART

The industrial-type test column employed has an internal diameter of 976 mm, is 5400 mm long, and is connected to a surface condenser of 200 m^2 area and a reboiler of 45 m^2 surface area. The column body contains a series of sample probe openings vertically spaced along it and, in the central part, two pairs of sight windows for visual observation. Up to five plates can be mounted in the column at varying plate spacings. A detailed description of the column regulation and operation has already been given (*5,6*), together with a discussion of the experimental procedures for determination of the sample concentrations, stream pressures and temperatures, and the column loading, expressed as the vapor velocity (*6,7*). When used in this work, the column could still function only at total reflux and essentially atmospheric pressure; it can now operate at arbitrary reflux ratios. The methanol–water test mixture pumped into the reboiler at the start of a series of measurements had a concentration of about 10 mole % MeOH. Samples were not taken from the top and bottom trays, which were considered to function as stream distributors, especially for the vapor flow across the column.

We carried out measurements of the efficiencies of the following plates: bubble-cap, sieve, Uniflux, APV-West of the downcomer type, and Ripple and Turbogrid (to a limited extent) of the type without downcomer. The geometrical and constructional characteristics of these plates are set forth in the appendix. The plate spacing chosen was 400 mm in all cases.

LIQUID AND VAPOR SAMPLING PROBES

In the overwhelming majority of publications devoted to experimental determinations of distillation plate efficiences, the authors employed only liquid sampling probes (*8*). In atmospheric columns the liquid is withdrawn through sampling tubes or directly from the column by gravity or by utilizing the slight gage pressure in the column, cooled and sampled.

Sampling with simple tubes or outlets located in the bottom of the downcomers is described in (*9–11*). Garner et al. (*12*) used an insulated sampling tube withdrawing from the upper part of the downcomer. The sample being taken then flowed into a separator from which the liquid either returned by gravity flow to the column or was sampled. (This procedure does not eliminate the possible effects on liquid sample composition of vapor carryover or formation in the downcomers.) Ellis and Shelton (*13*) withdrew liquid samples at the outlet weir of the downcomer; similarily, this procedure does not eliminate these vapor effects in the downcomers. Kirschbaum (*14*) withdrew liquid samples through insulated tubes from various points on the tray. In the Delaware A.I.Ch.E. report (*15*), liquid samples were withdrawn from both the downcomers and the trays themselves. In the former instance the sampling tube ended in a small trough mounted on a chord wall of the downcomer, while in the latter case the liquid was withdrawn from shallow circular depressions (ϕ 12.7 mm × 5 mm deep) in the surface of the plate through tubes connected to them.

For trays without downcomers, the liquid sampling tube may be connected to a small collecting cup mounted below the tray under a slot or holes or simply end just under such an opening in the tray through which the liquid drains. Huml (*6*) tested several variants of liquid samplers of these types. In some cases a cylinder of gauze 10 cm high was mounted over the sampling point to break the foam and ensure withdrawal of clear liquid, but this was found to be unnecessary.

The obtaining of representative vapor samples is much more complicated, and frequently papers where this problem is considered at all either essentially stop with the statement of its difficulty or concern experimental columns with only one plate, where a vapor sampler can be located far above the plate, thus greatly decreasing if not entirely eliminating the effect of liquid carryover. In several cases the vapor sampler used consisted of a simple tube ending in the vapor space above the tray often with the end bent down to face into the vapor flow and or with a traveling mounting (e.g. *16*). Ellis and Shelton (*13*) mounted their vapor sampling tube in the vapor riser with the opening facing the vapor stream. Shilling et al. (*17*) sampled the vapor locally to obtain data for the local efficiency by mounting a larger tube vertically above a bubble cap with the sampling tube leading from the larger tube's upper end. This tube was employed to limit the horizontal vapor mixing in the vapor space above the foam, and any large entrained drops were assumed to be caught on the inner wall of the tube before withdrawing the essentially dry vapor. This sampling probe does not, however, in any sense eliminate the possibility of nonadiabetic rectification between the liquid film draining down the inside wall of the tube and the vapor being sampled, where this liquid arises either from partial condensation of the vapor or by entrapment of the entrained droplets on the wall.

In vapor sampling with trays without downcomers, a vapor sampler in the form of an inverted funnel has been used, where the sampler could be located at a considerable distance above the plate (*18*). Huml (*6*) and Kaštánek (*8*) tested various types of vapor samplers in a preliminary effort in our project to try to develop a suitable probe. Most models took the form of inverted cups or funnels with the actual sampling tube leading from their upper end, either downward, from just inside the top of the closed cup, or upward from an opening in the cup top. In an effort to catch the entrained droplets, various types of baffles or metal wool were mounted in the lower end of the cup, before it was realized that the resulting surface also provided an excellent opportunity for mass transfer between the trapped liquid and the vapor being sampled. Further, various types of insulation were used on or over the cup to eliminate possible heat transfer through its surface and hence condensation of vapor within it. However, none of these early models was entirely satisfactory in yielding unchanged vapor samples without liquid carryover (*8*).

In our work reported here we used vertical cylindrical liquid sampling cups ϕ 15 × 20 mm high coaxially mounted on ϕ 4.5-mm copper sampling tubes, which had been previously annealed to facilitate bending during installation. The sampling cups were mounted by lugs to openings in the plate and insulated from it by a 5-mm layer of asbestos covered with Teflon foil. The cup and sampling tubes were also insulated with ϕ 8-mm asbestos cord and then wrapped with Teflon foil. The size of the cups was such as to permit any entrained vapor bubbles easily to rise from the liquid being sampled and escape, and the sampling cup and tube were thermally insulated from the plate and the surrounding vapor,

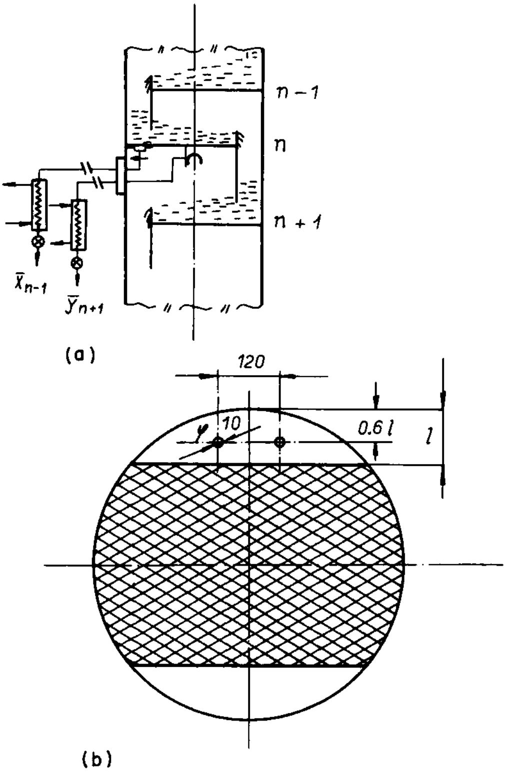


FIG. 1. Vapor and liquid sampler stations: (a) vertical section of installation on tray with downcomer; (b) horizontal tray section for liquid sampler positions on tray with downcomer.

which being virtually saturated and at a higher temperature than the liquid being sampled would otherwise cause it to boil, as it is also virtually saturated. The escape of any of the resultant vapor back into the column would leave a residual liquid sample enriched in the less volatile components. [It was found that with no insulation and with the liquid sample cooler (see Fig. 1a) removed, a vapor-liquid mixture spurted from the column with considerable force, indicating possible vapor blowback into the column as well.] With trays with downcomers, these liquid sample cups were mounted below ϕ 10-mm holes drilled in the bottom of the downcomers (i.e., in the lower plate), as shown in Fig. 1a and b. With trays without downcomers, these cups were mounted on the

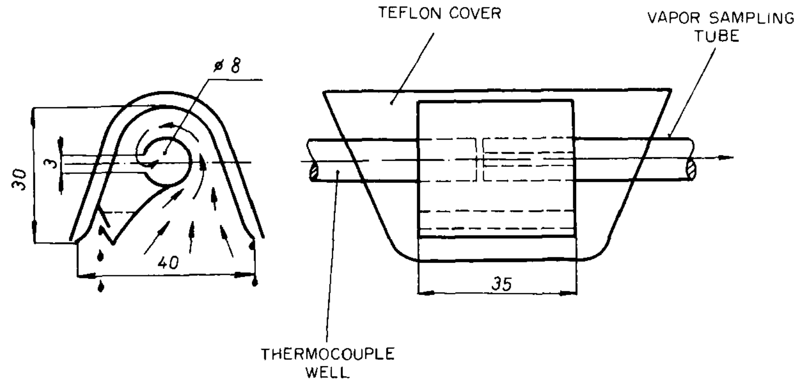


FIG. 2. Centrifugal vapor sampler Model J.

underside of the given plate; on Ripple trays they were mounted under a trough in the waved plate, and on Turbogrid trays, under a slot. With such trays the sampling cup serves the further function of providing a liquid reservoir seal during periods when the liquid on the tray is not draining through that sampling point on the plate so as to prevent vapor being inadvertently withdrawn during such a period.

Vapor sampling probes must, as has been said, sample only dry vapor and thus eliminate from the vapor sample both entrained liquid drops and liquid spray weeping from the upper tray or, in the case of trays without downcomers, the draining main liquid stream. The final vapor sampler evolved for mounting below a plate which is of open horizontal cylindrical shape is shown on Fig. 2 and is based on the application of centrifugal force for effecting the rapid and clean separation of the vapor sample from any entrained liquid droplets from whatever source. A vapor stream enters the mouth of the sampler from below and is accelerated and drawn into a circular path at the top of the sampler before being withdrawn from it through a longitudinal slot in the sampling tube mounted along the axis of the sampler. The liquid drops are thrown to the inside of the sampler jacket by the resulting centrifugal force and either drain back to its right lip or collect in the liquid trap at the left side of the sampler forming a liquid seal, which permits the liquid accumulating there to drain through the trap slot outlet. To prevent heat exchange with the surroundings and especially draining or weeping liquid and hence phase changes in the vapor being sampled, the sampler proper was covered with a jacket of sheet Teflon and the sampling tubes insulated as described for the liquid sampler. This type of sampler also permits the installation of a thermocouple well coaxial with the vapor-withdrawal tube, as shown in Fig. 2, and both tubes are mounted in sleeves in the sampler with insulating seals so that there is no direct metal-to-metal thermal contact between them. The dimensions of the sampler were chosen so that, on the one hand, no critical dimensions would be so small that working gaps in the sampler could be bridged by liquid under the influence of surface tension but, on the other hand, so that the residence time of the vapor in the sampler would not be more than a few per cent of its residence time in the foam on the tray below, to limit the possible contact and exchange between the vapor being sampled and the liquid droplets being separated from it. As a result, the over-all dimensions of the sampler must range from those shown in Fig. 2 as a maximum to about half that size as a minimum.

This vapor sampler, as well as a number of earlier models (8), was tested in a hydraulic section (see Fig. 3) for its ability to trap out entrained liquid droplets of salt solution from the air stream being sampled. This vapor sampler ranked among the best from the entrainment point of view and gave nearly complete vapor-liquid separation over a wide range of vapor velocities, provided the foam level did not come nearer than about 5 cm from the sampler mouth. (Most other models gave incomplete separation even earlier.) These vapor samplers were therefore always mounted as near the upper plate as possible, and near vapor inlet passages, but we do not consider it possible to obtain representative vapor samples with them when the foam level is less than 10 cm from the upper

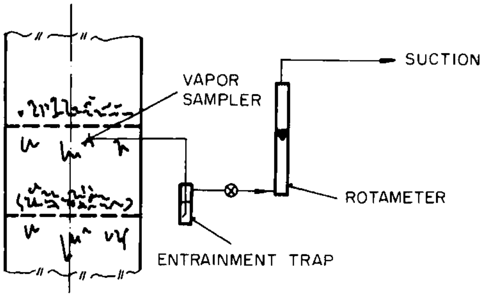


FIG. 3. Test setup for measuring liquid carryover in vapor sampler.

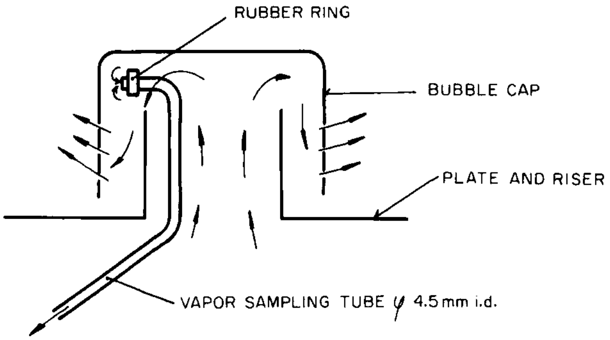


FIG. 4. Vapor sampler for bubble-cap tray.

plate. The efficiency of the thermal insulation of the various models of the vapor samplers was also tested on a special apparatus (8) which functioned as a plate of a small column. The chosen type (as well as a number of others employing Teflon or glass jackets) was satisfactory from this point of view as well. The chosen type was also among the simplest from the point of view of internal elements on which vapor-liquid contact could occur.

This vapor sampler was used on all the plates tested except the bubble-cap tray, which was tested before the development of this sampler was completed and for which it is not really essential. Here a simple bent copper tube was mounted in the vapor riser as shown in Fig. 4. The change in direction of the vapor stream in flowing from the riser to the annulus between it and the bubble cap provides the centrifugal force for separating the entrained liquid droplets from the vapor stream, so that it is necessary only to take advantage of this effect and to prevent drag of any liquid caught on the sampling tube by the vapor stream to the tube's mouth. For this purpose a short silicone rubber ring was mounted near the mouth of the tube. We found that even more perfect blocking of this creep flow would be necessary, say by the use of a series of such rings or of a tube with a U bend at the end with the mouth facing into the vapor flow.

EVALUATION OF CARRYOVER AND WEEPING

In our review article (2) we have surveyed the literature on the effect of liquid carryover on tray efficiency as well as the hydraulics of this entrainment. As we expected, the nonuniformities in tray hydraulics in our large experimental column led to significant liquid carryover, especially at heavier tray loadings.

In contrast, very little of a quantitative nature is available in the literature on the corresponding effect of liquid weeping on tray efficiencies or on the hydraulics of this weeping on trays with downcomers (*8*). Again, however, we found that nonuniformities in the tray hydraulics in our large column (hydraulic gradient across tray, pulsations in stream flows, etc.) led to significant liquid weeping, especially at low tray loadings on trays without positive liquid seals (e.g., sieve and Glitsch), as could be observed visually (*19*).

We assumed that we could neglect the effect of dumping where the liquid weeping occurs near the inlet to the tray at very high tray loadings, so that with the normal cross-flow tray construction, the liquid bypassing the given tray does not even mix with the liquid on the tray below but passes directly to the outlet downcomer of this lower tray and hence in effect bypasses two trays at once.

As discussed in our previous theoretical paper (*1*), the relative liquid carryover from plate to plate can be calculated from the relation

$$e_n^{+\prime} = \left(\frac{\bar{y}_n - \bar{x}_{n-1}}{\bar{x}_{n-1} - \bar{x}_n}\right) - \left(\frac{x_D - \bar{x}_{n-1}}{\bar{x}_{n-1} - \bar{x}_n}\right)(1 - R_n') \qquad \text{(VIII-18)}$$

where

$$e_n^{+\prime} \equiv \dot{E}_n^{+\prime\prime}/\dot{V}_n' \qquad \text{(VIII-17)}$$

if no other entrainment occurs, assuming well-mixed tray contents. For total reflux, the only case we are considering here, the last term in the right member vanishes. Similarly, if we have only liquid weeping, we find from Eqs. (VIII-8), (VIII-10), (VIII-16), and (VIII-20) in that paper that

$$e_{n-1}^{-\prime} = \left(\frac{\bar{y}_n - \bar{x}_{n-1}}{\bar{x}_{n-2} - \bar{x}_{n-1}}\right) - \left(\frac{x_D - \bar{x}_{n-1}}{\bar{x}_{n-2} - \bar{x}_{n-1}}\right)(1 - R_n') \qquad (1)$$

where

$$e_{n-1}^{-\prime} \equiv \dot{E}_{n-1}^{-\prime\prime}/\dot{V}_n' \qquad (2)$$

is the relative weeping. Again the last term in the right member vanishes at total reflux. The separate application of these relations in practice is usually well justified, as weeping (which can only exist on trays with downcomers) is usually significant only at low tray loadings, while carryover is important on the contrary only at high tray loadings.

Another type of liquid "entrainment," which has so far usually not been considered, may be termed "induced weeping." [It has, however, been discussed qualitatively by Ellis and Shelton (*13*).] As industrial column internals are constructed of thin metal sheet, we may expect heat transfer to occur through, for example, the tray itself, the downcomers, etc., whenever there is a temperature difference between the streams on the two sides of these walls. Thus the vapor rising along the downcomer wall will partially condense on it, as it is cooled by the liquid flowing from the upper plate through the downcomer. Similarly, a part of the vapor entering the vapor openings in the tray itself will also condense on the tray undersurface as the latter is cooled by the liquid on it. The vapor formed in the downcomer or on the tray by the corresponding condensation of the vapor on the other side of the metal surface will usually combine with the main vapor stream after separation from the liquid on the upper tray and be measured with this stream, but the liquid condensate formed will normally drain back or fall to the lower tray as a weeping stream. The quantitative analysis of this case can be formally described by the general relations presented earlier and hence by Eq. (1).

We expect that the rate of heat transfer through these metal surfaces and hence the rate of condensation and vaporization will not vary greatly with the tray loading, as the fluid heat transfer coefficients, being very large, will not be controlling. Thus the relative induced weeping $e_{n-1}^{-\prime}$ and the concentration deviation $\bar{y}_n - \bar{x}_{n-1}$ for total reflux will be greatest for low tray loadings, as was found to be the case even with trays such as bubble-cap, APV-West, and Uniflux, where ordinary weeping cannot be expected at low loadings, as these trays provide positive liquid sealing. In this connection Ellis and Shelton present results showing a relative decrease in the effect of induced weeping with increasing vapor velocity by comparing the vapor composition in a riser with the liquid concentration at the outlet weir on the same plate. They assume that the liquid leaving the downcomer after partial vaporization in it would have the same composition as the vapor entering the riser above and state that some unpublished results support this assumption. (Actually the liquid leaving the downcomer would mix with and be diluted by the condensate formed on its vapor side.)

DETERMINATION OF ENTRAINMENT FROM CONCENTRATION DATA AND COMPARISONS WITH OTHER CORRELATIONS TRAYS WITH DOWNCOMERS

Values of entrainment obtained from Eq. (VIII-18) [or Eq. (1), as appropriate] were compared in the former case with those calculated from the correlations of the A.I.Ch.E. program (*20*), Jones and Pyle (*21*), and Hunt et al. (*22*), which were selected on the basis of the discussion we presented in (*2*). It is well to emphasize here that the existing correlations of carryover are not adequate, as they usually correlate well only the data of the correlation's author(s). They employ different correlating parameters and variables and the differences among these correlations are significant to large, as is the scatter of the experimental data itself. Most of these correlations apply to bubble-cap or sieve trays, but we were forced to apply them to other types of trays as well, for lack of specific data on the latter.

Jones and Pyle (*21*) measured carryover for bubble-cap trays with the mixture acetic acid–water. These data are near those for Hunt et al. (*22*) (even though the latter correlation was originally proposed for sieve trays) and characterize well the carryover dependence measured by other authors (*20*). Since several authors (*2*) state that surface tension is an important physicochemical parameter in determining carryover, and since the surface tension of the acetic acid–water system is close to that for the methanol–water mixture, we preferred the correlations of these authors for comparison purposes, as there is no agreement in the literature on the exact influence of surface tension. The graphical correlation of carryover of the A.I.Ch.E. program (*20*) was considerably higher for almost all the data of these authors which was used for comparison (with the exception of the data cited in the A.I.Ch.E. program itself), but it was also utilized for preliminary orientation comparisons.

Uniflux Trays (Fig. 5)

The dependence of the liquid carryover on the plate loading (F factor) is well expressed by the Jones and Pyle relation. The rather high experimental values which we obtained can be explained partly on the basis of the fact that the relation of these authors was obtained for a plate spacing of 42.5 cm, which is slightly

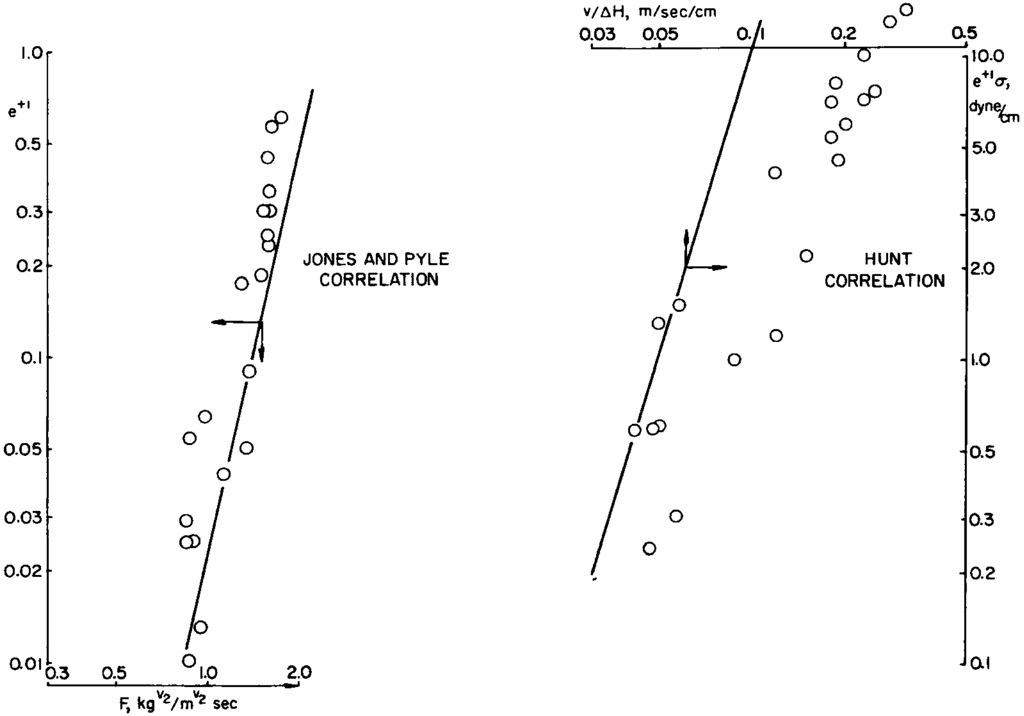


FIG. 5. Correlation of liquid carryover on Uniflux tray: left, with Jones and Pyle correlation shown as curve; right, with Hunt correlation shown as curve.

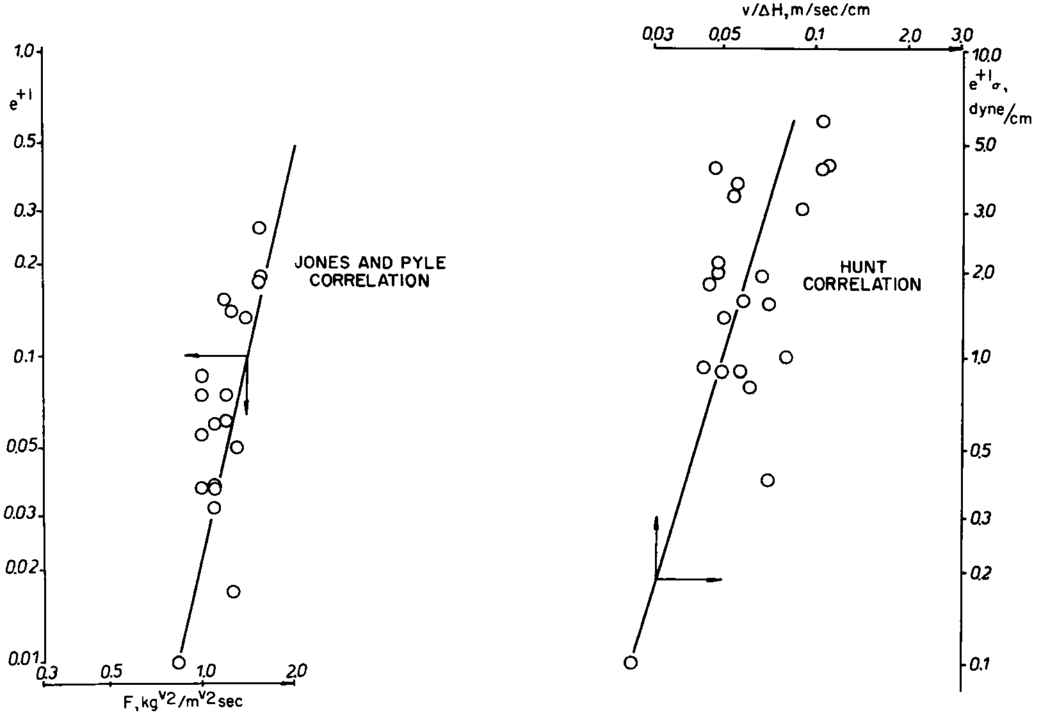


FIG. 6. Correlation of liquid carryover on APV-West tray: left, with Jones and Pyle correlation shown as curve; right, with Hunt correlation shown as curve.

larger than our spacing, but mainly because the unidirectional flow of the vapor from the tray slots leads, as can be observed visually, to a considerable arclike spraying of the liquid from the foam in this direction, which contributes to a higher carryover than with, for example, bubble-cap trays. There is a large deviation from the Hunt correlation, especially at higher velocities; a similar deviation was observed by tunnel caps by Atteridg et al. (23).

APV-West Trays (Fig. 6)

The carryover dependence is in agreement with the Jones and Pyle relation and also with the Hunt correlation. The latter agreement can be expected, as the APV-West tray is, in fact, a combination of a sieve and a bubble-cap tray, and the Hunt correlation was found to be successful for both of the latter types of trays.

The considerations presented above concerning weeping (especially induced weeping) were experimentally confirmed with both

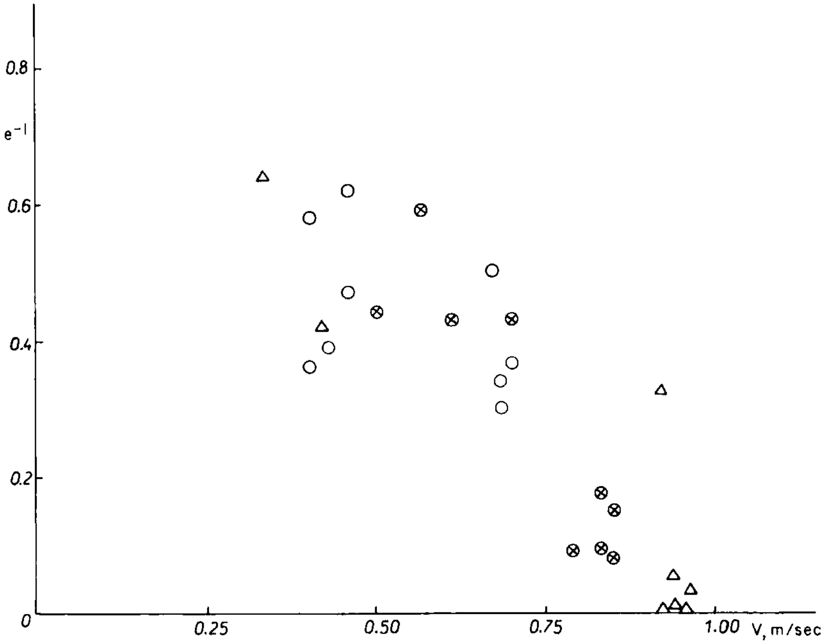


FIG. 7. Dependence of liquid weeping on vapor velocity: ⊗, Uniflux tray; △, APV-West tray; ○, bubble-cap tray.

these trays. Significant differences between the vapor and liquid concentrations were found with the APV-West tray in the two experiments with the lowest vapor velocity at which it was still possible to maintain a steady regime in the column. Similarily, with the Uniflux tray, concentration differences were found at the lowest vapor velocities employed. Values of the relative weeping calculated according to Eq. (1) from the data for these plates are shown on Fig. 7 in dependence on the vapor velocity. In view of the agreement of the data for these trays with positive liquid seals, we may assume that we are dealing mainly with induced weeping. Further, at medium vapor velocities, when the effects of induced weeping would not be expected to be important and the effect of carryover was not yet significant, we found, in agreement with expectation, very good agreement between the vapor and liquid concentrations (i.e., $\bar{y}_n \doteq \bar{x}_{n-1}$). The above data on liquid carryover thus correspond to the region of high vapor velocities, where, again $\bar{y}_n > \bar{x}_{n-1}$.

Sieve Trays (Fig. 8)

It is usually assumed that sieve trays have a lower but similar carryover to that for bubble-cap trays (*2, 21*). On analyzing the samples withdrawn from our sieve tray, we were, however, surprised to find that the vapor samples were significantly richer than the liquid samples (i.e., $\bar{y}_n > \bar{x}_{n-1}$) over the whole range of vapor velocities employed. While liquid carryover would explain this result at high plate loadings and weeping (normal or induced), at low loadings, as with Uniflux and APV-West trays, we did not expect these deviations in the middle (i.e., normal working) range of vapor velocities. This result was so unexpected that we repeated the measurements later with the same results. The apparent liquid carryover calculated from Eq. (VIII-18) is shown in Fig. 8.

In the range of low vapor velocities we directly observed on repetition of the experiment a significant continuous weeping from the plate, as expected. At higher vapor velocities, however, the weeping continued but became intermittent and occurred mainly near the column walls, as a result of density pulsations and oscillations in the foam on the tray, presumably as with Turbogrid trays (*24*). The interpretation of our measurements was further complicated by the fact that at lower vapor velocities the calculated values of liquid carryover differed somewhat on the two plates from which complete and reliable samples were taken, but in all cases the apparent carryover which decreased with increasing tray loading was greater than that calculated by the Jones and Pyle and Hunt correlations, indicating significant weeping over the whole range of vapor velocities. This residual weeping, however, sharply decreased with increasing tray loading and apparently was approaching zero at the highest tray loadings employed, as can be seen in Fig. 8 [cf. Eq. (1)]. We were thus not able to check these correlations for this tray, as our results were not adequate for permitting simultaneous evaluation of carryover and weeping, for which we would, for example, need extremely accurate data from two adjacent trays under conditions where we could assume constant relative carryover and weeping from tray to tray. We believe instead that it would be advantageous to make direct hydraulic or dilution measurements of both the carryover and weeping from sieve trays, especially those of large diameter, so as to clarify this question.

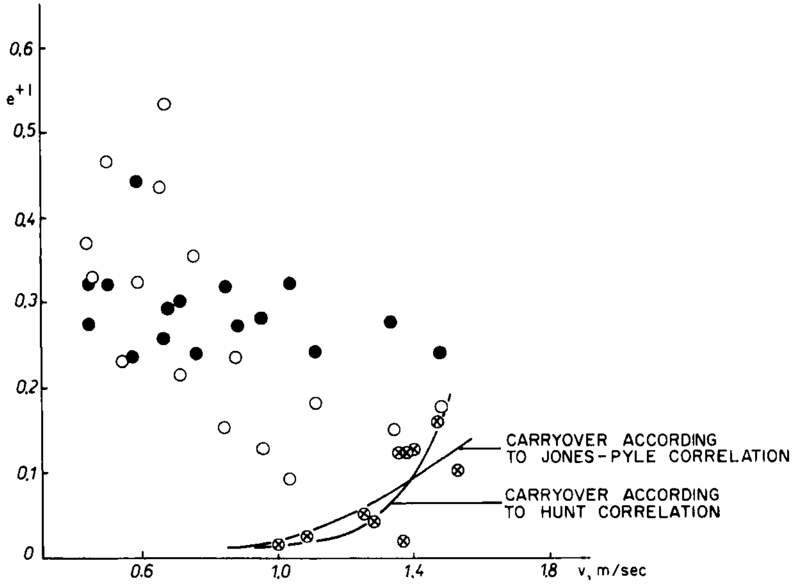


FIG. 8. Correlation of apparent liquid carryover on sieve tray: ○, data from third tray; ●, data from fourth tray; ⊗, carryover calculated according to Hunt correlation.

Bubble-cap Trays

As expected, at low vapor velocities (below 0.8 m/sec) we found that $\bar{y}_n > \bar{x}_{n-1}$, indicating weeping. The results are shown in Fig. 7. The foam height was about 8 cm and the vapor flow had a pulsating character. At very low vapor velocities (about 0.45 m/sec) the row of bubble caps at the liquid inlet functioned very irregularily, and we observed that liquid collected on the underside of the tray at the corresponding vapor risers, indicating direct weeping. (It should be noted that the sampler tube we employed with this tray would collect slugs of liquid and hence give false readings if liquid dumped even intermittently through the vapor riser in which it was mounted.) In the range of medium tray loadings ($v = 0.8$ to 1.2 m/sec), the agreement between the vapor and liquid concentrations sampled was very good, indicating negligible weeping and/or carryover, again in accordance with expectations.

At vapor velocities above about 1.2 m/sec, however, we found $\bar{y}_n < \bar{x}_{n-1}$ (that is, apparently "negative" entrainment) up to the highest loading measured, $v = 1.6$ m/sec. We were forced to attribute this discrepancy to creeping of liquid trapped on the outside of the sampler tube and dragged along it to its mouth by the vapor flow in the riser, where it was then sampled with the vapor. As already indicated, even the mounting of a guard ring near the mouth was not sufficient to eliminate this liquid entrainment in the vapor sample at these higher velocities, when the distance between the top of the foam layer and the next higher tray was about 14 cm.

A second experiment was made with the bubble-cap tray deliberately installed at a slant of 2 cm from level to test the effect of installation errors. The same tube samplers were used and the mutual dependence of the vapor and liquid concentrations indicating the presence or absence of entrainment, was similar to that for the level trays except that the weeping region was larger in the former case, undoubtedly because of the greater ease of liquid backflow through the vapor risers at the lowest point on the tray. Thus weeping still occurred on the slanted tray at vapor velocities where it had already ceased on the horizontal tray (*8*).

Unfortunately, because of the press of other work, it was not possible later to retest this bubble-cap tray with an improved vapor sampler at these higher vapor velocities to compare the hydraulic correlations of carryover and our measurement procedure.

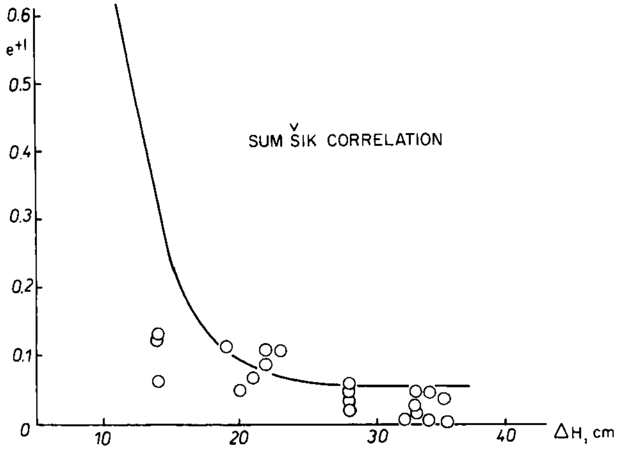


FIG. 9. Correlation of liquid carryover on Ripple tray, Sum-Šik correlation shown as curve.

TRAYS WITHOUT DOWNCOMERS

Ripple Tray (Fig. 9)

So far there are very few correlations of carryover available for comparison with trays without downcomers. For large-diameter columns there are the correlations of Sum-Šik et al. (25) and Kasatkin et al. (26). The Kasatkin relation requires a knowledge of the foam porosity, which was not measured directly in our experiments, as we did not measure the liquid holdup. We therefore used the Sum-Sik correlation for comparison with our measured values of carryover. Our values are lower, especially at low vapor velocities (i.e., high ΔH). In this connection it should be pointed out that this correlation predicts a constant carryover of 0.056 kg/kg at the lowest vapor velocities, whereas in fact it undoubtedly goes to zero; further, this limiting value is really quite large, especially for this type of tray, where we expect a relatively low carryover at a given vapor velocity in comparison with other trays, especially of cross-flow type with greater foam nonuniformities.

Turbogrid Trays

Only a few measurements were made on Turbogrid trays in this series of experiments, mainly to test the effect of fluctuations in the vapor flow rate at fairly low vapor velocities, where significant carryover was not to be expected. Not surprisingly, the vapor and liquid concentrations agreed, with good accuracy (i.e., $\bar{y}_n \doteq \bar{x}_{n-1}$).

In summary we may say that while few data are available in the literature on weeping rates, especially for large columns, the data on carryover in the literature usually obtained by hydraulic or dilution methods in "cold" columns or sections usually show as large a scatter as do our data obtained by concentration measurements on actual ("hot") columns under normal operating conditions, and the correlations of these carryover data frequently show as large deviations from each other as do our data from them (with the exception of sieve trays, of course).

The development of stream samplers, especially for vapor, should continue with a view to further reducing their size as far as possible and allowing them to be mounted closer to the upper plate so that they can be used at still higher vapor loadings (higher foam levels), where the effect of carryover is greatest. It will also be necessary to develop more accurate models of tray action so as to take account of the degree of liquid mixing on the tray, to be able to distinguish between the true hydraulic entrainment and the reduced effective entrainment occurring in our relations (*1*). Further development will also be needed to enable accurate stream temperatures to be measured, as extremely accurate values are needed to determine the degree of saturation of the streams. The experiments we made in this regard during the research reported here (*8*), where we employed Cu-constantan thermocouples installed in copper tubes of the same size as the sampling tubes for liquid and vapor and mounted directly in the samplers themselves (see Fig. 2), were inconclusive and hence will not be presented here. Despite an adequate sensitivity and accuracy of measurement (about ± 0.1°C), the turbulent temperature fluctuations recorded by the probe were so large as to preclude accurate evaluation of the results. At most we can say that the streams appeared to be saturated—or sometimes apparently slightly supersaturated—although we are loath to accept the latter conclusion.

PLATE EFFICIENCIES

In evaluating the efficiencies of these trays from our concentration data, we have employed three types of tray efficiencies, which are expressed, as is common, in terms of vapor concentrations, with the assumption of constant reduced or actual vapor flow rates. This assumption is closely fulfilled under our conditions, as the heat losses from the insulated column are very small (5,7), the streams are virtually saturated, and we have used pseudomolal concentrations and flow rates:

1. The reduced efficiency, (*1*)

$$\bar{E}'_y \equiv \frac{\bar{y}'_n - \bar{y}'_{n+1}}{\bar{y}'^{*}_n - \bar{y}'_{n+1}} \tag{3}$$

where the equilibrium reduced vapor concentration is evaluated for the appropriate reduced liquid composition.

2. The apparent efficiency,

$$\bar{E}_y \equiv \frac{\bar{y}_n - \bar{y}_{n+1}}{\bar{y}^{*}_n - \bar{y}_{n+1}} \tag{4}$$

where the equilibrium vapor concentration is evaluated for the appropriate actual liquid composition.

3. The conventional efficiency,

$$E_y \equiv \frac{(\bar{y}_n) - (\bar{y}_{n+1})}{(\bar{y}^{*}_n) - (\bar{y}_{n+1})} \tag{5}$$

The meaning of the symbols is explained below.

With the reduced efficiency, we work with the (straight) reduced operating line on the *yx* diagram, and for simple carryover and weeping we project the measured vapor compositions horizontally to this line, giving the reduced vapor values unchanged. We can then read off the corresponding reduced liquid concentrations, as explained in (*1*). The apparent efficiency is obtained by using the actual vapor and liquid concentrations, i.e., by using the actual operating line, which is always curved. This situation causes no difficulties when evaluating the experimental data but requires the use of suitable and more complicated graphical methods than usual when calculating from plate to plate (*2*,*27*). As we have showm (*1*), the conventional procedure for determining plate efficiencies involves projecting the actual liquid concentrations vertically to the reduced operating line, from which we read off the corresponding vapor concentrations $(\bar{y}_n)$. Thus for total reflux $(\bar{y}_n) = \bar{x}_{n-1}$. As we have shown, this procedure is incorrect in the presence of liquid entrainment, i.e., is not consistent with the material balance relations for the plate.

While the reduced liquid plate efficiency is simply related to the reduced vapor value (*1*), the same cannot be said for the apparent efficiency, while the conventional efficiency, being based on an incorrect procedure, does not really allow one to speak of a consistent relation between the vapor and liquid efficiencies. We have discussed elsewhere the predilection to use the vapor efficiency in practice (*28*). This preference, in the case of the reduced efficiency, has no objective basis, as the efficiencies for the two phases are equivalent; in fact, the same is true of the apparent efficiency.

Plate efficiencies are further classified according to the way in which the equilibrium composition (here $\bar{y}_n^*$) is defined. In the Murphree model, we take this vapor to be in equilibrium with the liquid leaving the tray, so that we have:

For the reduced efficiency: $\bar{y}_n'^* = \bar{y}_n'^*(\bar{x}_n')$ (3′)

For the apparent efficiency: $\bar{y}_n^* = \bar{y}_n^*(\bar{x}_n)$ (4′)

For the conventional efficiency: $(\bar{y}_n^*) = \bar{y}_n^*(\bar{x}_n)$ (5′)

In our generalization (*1*) of the Hausen efficiency (*29*), we shall only be concerned with the reduced case. In the definition of the theoretical (i.e., equilibrium) tray, we assume that the entering reduced streams are the same as on the real tray, but that the exit-reduced streams are mutually in phase equilibrium. As this efficiency was introduced (*30*) to be consistent with the material balance relations, there seems to be no point in elaborating its "apparent" and still less its "conventional" variants.

The conventional efficiency is reported despite its faults, as virtually all the efficiency data in the literature are actually for this inconsistent model. The use in practice of the other efficiencies, especially the reduced one, will require the development of consistent detailed models of tray action in terms of liquid mixing, entrainment, and mass-transfer coefficients, so that consistent values of the latter, for example, can be obtained from experimental data.

EVALUATION AND COMPARISON OF PLATE EFFICIENCIES

While it is comparatively easy to state the accuracy of our analytical concentration determinations (±0.2 mole %), it is considerably more difficult to give a representative average figure for the accuracy of the efficiencies calculated from them, mainly because of uncertainties in the vapor-liquid equilibrium data. A figure of ±5% *represents our estimate of this value.*

Murphree Efficiencies

The three Murphree efficiencies were evaluated for the trays Uniflux, APV-West, bubble-cap, sieve, and Ripple, and the results presented as dependences on vapor velocity in Figs. 10 to 14. (The partial results for the Turbogrid tray are not shown, as they were obtained in the region where the carryover was nearly negligible, so that these efficiencies closely agree.)

We found for all the plates measured that the values of the conventional and reduced Murphree plate efficiencies are about the same, with the exception of the range of highest vapor velocities for some plates, especially Uniflux. This result, if general, will have considerable practical importance, as it will mean that we can, at least in preliminary calculations, use the data published in the literature as though they were for the reduced efficiencies, while taking account of carryover or weeping, assumed to be known, by the procedure outlined earlier (*1*). The deviations between these efficiencies, especially at the highest vapor loadings, cannot be considered to have been decisively proved in view of the scatter of the experimental data, but such a difference is not unexpected, as the diluting effect of carryover is greatest there. It is, therefore, somewhat surprising that there is so little difference between these efficiencies for the sieve tray where, as we have seen, there is heavy weeping at low and medium tray loadings, as well as substantial carryover at the highest.

The situation is quite different with regard to the apparent efficiency, whose values for all the trays measured over the ranges of tray loadings at which we were able to take representative vapor (and liquid) samples usually differ, and often substantially, from those of the other two efficiencies. As is to be expected, this difference is greatest for the ranges with significant weeping (or induced weeping) or carryover but *statistically insignificant* where they are negligible. The apparent efficiency is greater than the reduced efficiency since for the former the denominator is smaller ($\bar{y}_n'^{*} > \bar{y}_n^{*}$ since $\bar{x}_n' > \bar{x}_n$), while the numerator is the same as in the latter case. The differences are largest for the sieve tray (for heavy weeping) and the Uniflux tray (for heavy carryover). The existence

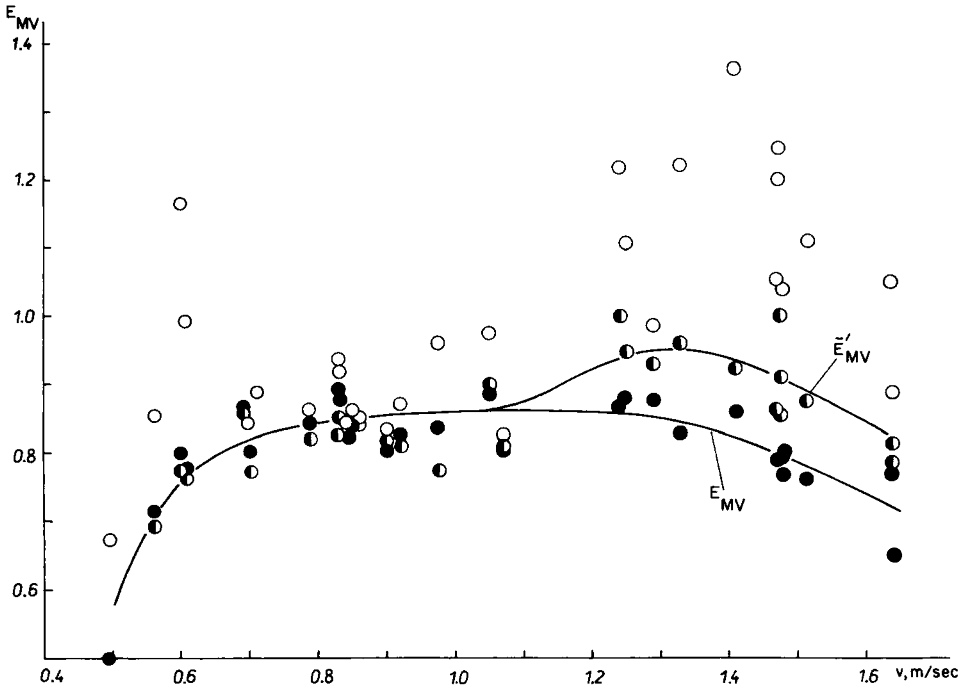


FIG. 10. Dependence of Murphree-type plate efficiencies on vapor velocity for Uniflux tray: ○, apparent efficiency $\bar{E}_{MV}$; ●, conventional efficiency E_{MV}; ◐, reduced efficiency $\bar{E}'_{MV}$.

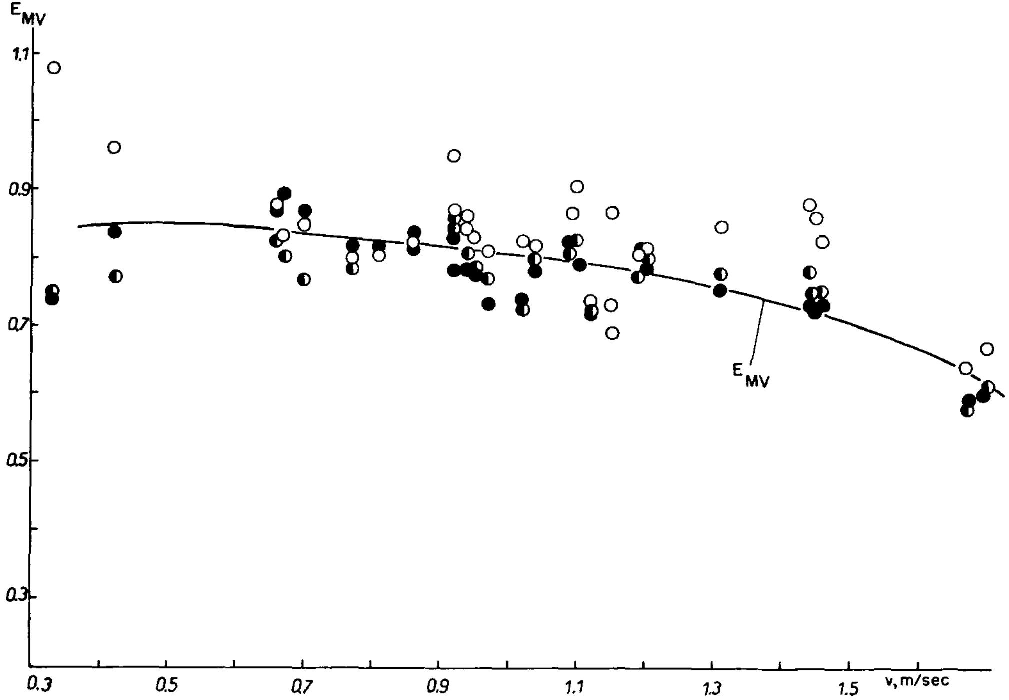


FIG. 11. Dependence of Murphree-type efficiencies on vapor velocity for APV-West tray; ○, apparent efficiency $\bar{E}_{MV}$; ● conventional efficiency E_{MV}; ◐, reduced efficiency $\bar{E}'_{MV}$.

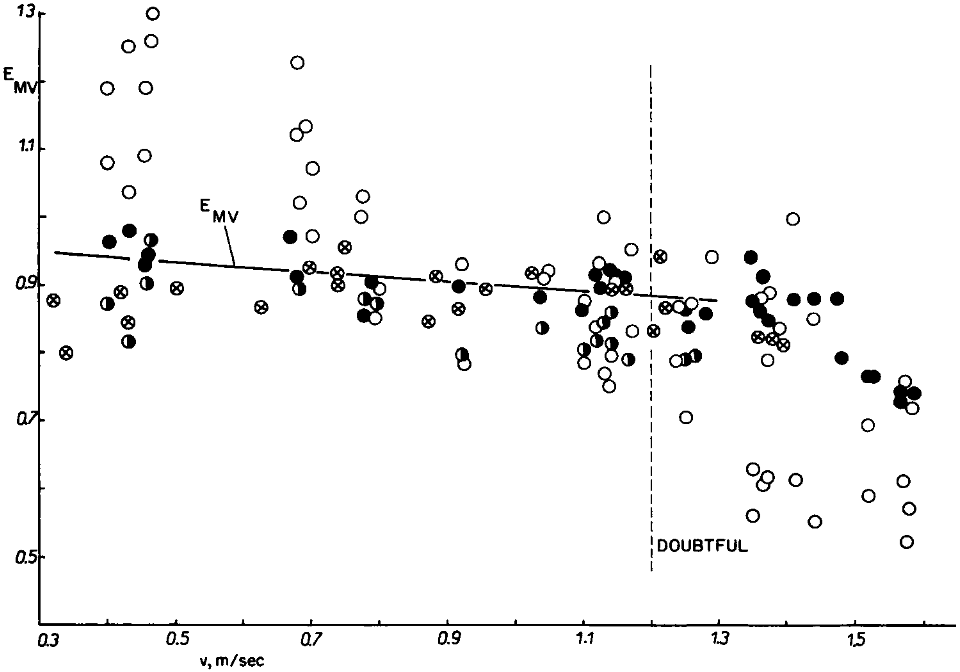


FIG. 12. Dependence of Murphree-type efficiencies on vapor velocity for bubble-cap tray: ○, apparent efficiency, level tray, $\bar{E}_{MV}$; ●, conventional efficiency, level tray, E_{MV}; ◐, reduced efficiency, level tray, $\bar{E}'_{MV}$; ⊗, conventional efficiency, slanted tray, E_{MV}.

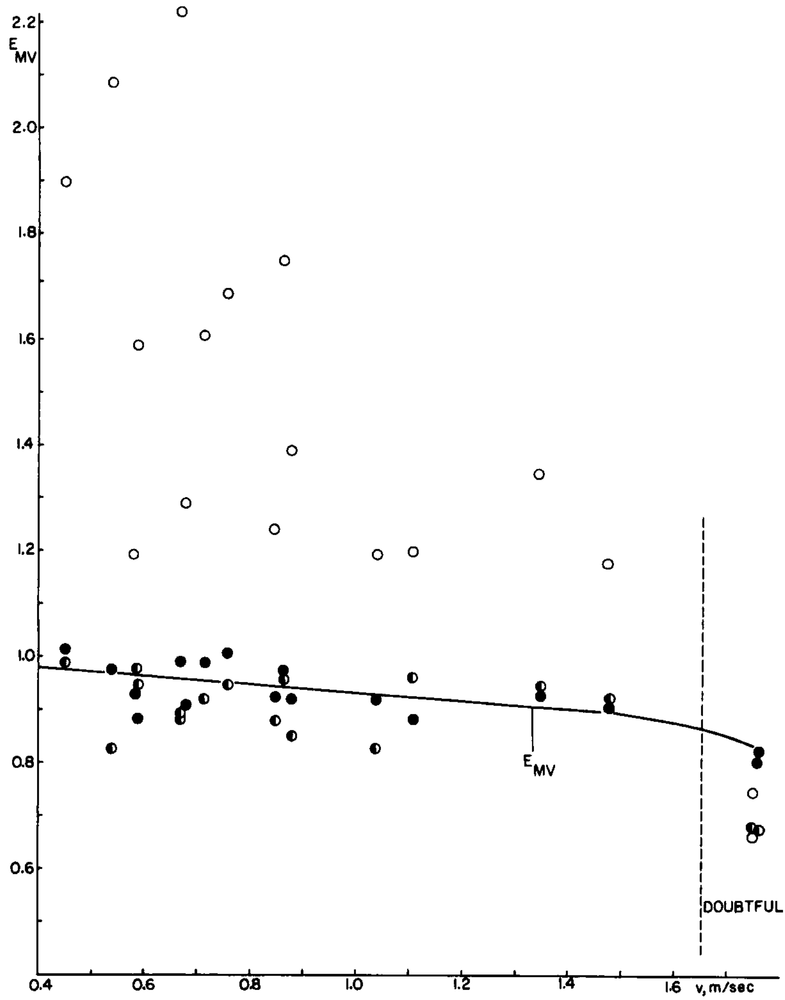


FIG. 13. Dependence of Murphree-type efficiencies on vapor velocity for sieve tray: ○, apparent efficiency $\bar{E}_{MV}$; ●, conventional efficiency E_{MV}; ◐, reduced efficiency $\bar{E}'_{MV}$.

of large differences between these apparent efficiencies and the other two types was also found for Glitsch trays (*19*), especially at low tray loadings, where significant weeping through the tray openings was confirmed by visual observation, in agreement with the results for sieve trays.

Even though we consider these apparent efficiencies to have few

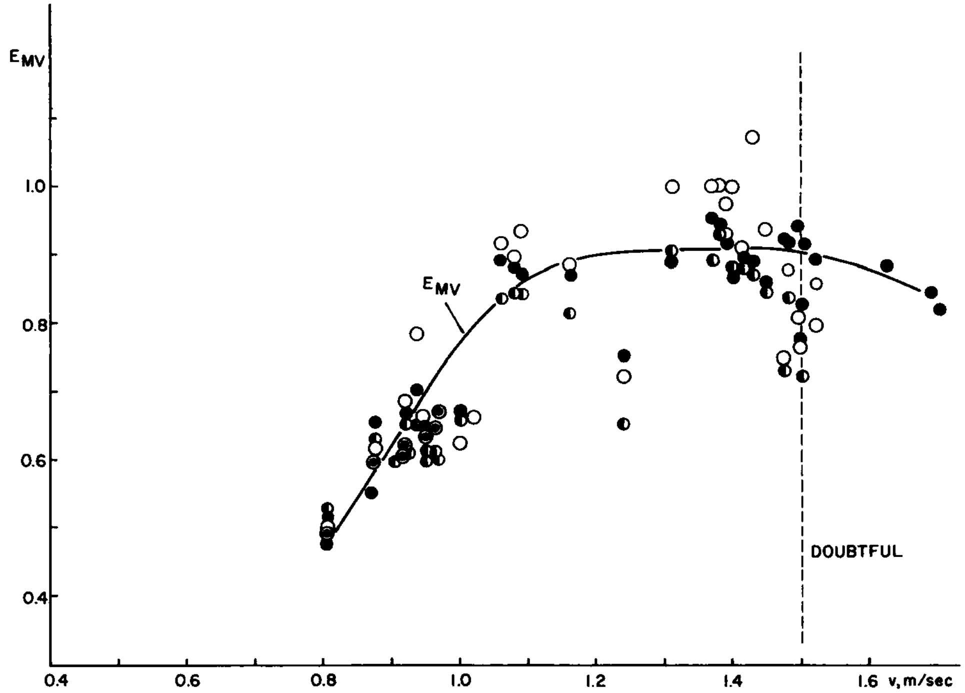


FIG. 14. Dependence of Murphree-type efficiencies on vapor velocity for Ripple tray: ○, apparent efficiency $\bar{E}_{MV}$; ●, conventional efficiency E_{MV}; ◐, reduced efficiency $\bar{E}'_{MV}$.

advantages and a number of disadvantages, the differences between their values and those for the reduced and conventional efficiencies show that we may not ignore the liquid entrainment streams between plates in distillation (and absorption) columns, as has been done previously in defining plate efficiencies. Even where the values of these plate efficiencies do not differ greatly, as is the case here with the conventional and reduced types, we cannot ignore the presence of entrainment when calculating the number of plates necessary in the column or when evaluating mass-transfer coefficients from the experimental plate efficiencies. Thus it is, for example, necessary to regard the published values of these coefficients, obtained from the conventional efficiencies usually without taking carryover into account in any way, with some reserve.

While the constructional differences among these trays preclude any simple quantitative comparison, these plots of the various tray efficiencies against vapor velocity (tray loading) permit not only mutual comparison of these efficiencies under similar conditions but give a graphical expression to the practical question of the operating range of each tray with good efficiency, as can be read from these figures.

There is no other especially pressing reason for expressing the tray efficiencies in this way, and we find that much of the scatter of the data when plotted this way is due to the fact that the foam height and hence pressure drop across the tray may differ significantly at a given tray loading (*8*). We may accordingly also compare tray efficiencies in dependence on pressure drop across the plate, as shown on Fig. 15 for the conventional Murphree efficiencies, from which further obvious comparisons of these trays may be directly read off. It is interesting to note that the intersection of the curves for Ripple, bubble-cap, and sieve trays (91% and 38.5 mm H_2O) corresponds to vapor velocities of 1.32, 1.08, and 0.67 m/sec, respectively.

The slanted bubble-cap tray (2 cm in 1 m) had, except at the lowest velocities, virtually the same conventional Murphree efficiency as the horizontally mounted plate (cf. Fig. 12). The lower value for the slanted tray at the lowest vapor velocities is to be expected, as the vapor would preferentially pass through the highest vapor risers when the liquid level is low and hence nonuniform.

We found, rather against our expectation, that alternating increases and decreases of the process steam pressure in the reboiler, leader to 20% changes in the vapor flow rate from its mean value

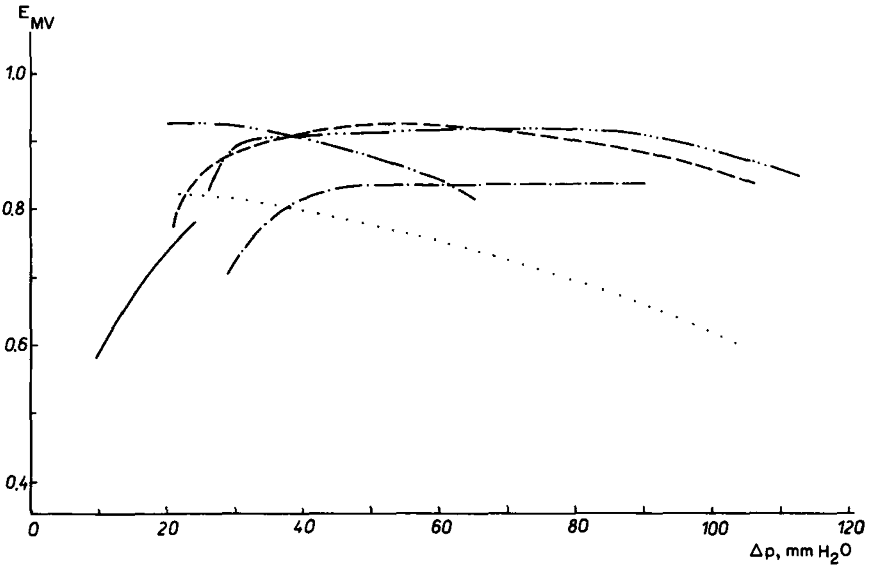


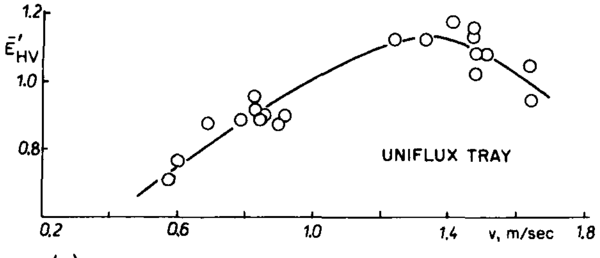
FIG. 15. Dependence of conventional Murphree plate efficiency on pressure drop across tray; ———, Turbogrid tray; ...———, sieve tray; .———, Uniflux tray; — — —, Ripple tray; ..———, bubble-cap tray; ...., APV-West tray.

over a 4-min period, had no apparent effect on the Turbogrid tray efficiency, except at the very lowest columns loadings (and hence foam heights).

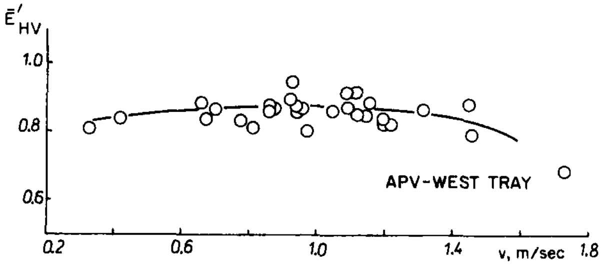
One of the very few disadvantages we observed with the Ripple tray was a certain tendency toward fouling of the tray holes by solids or corrosion products which accumulated during the intermittent operation of the column with the methanol–water mixture over a period of several weeks.

Generalized Hausen Efficiencies

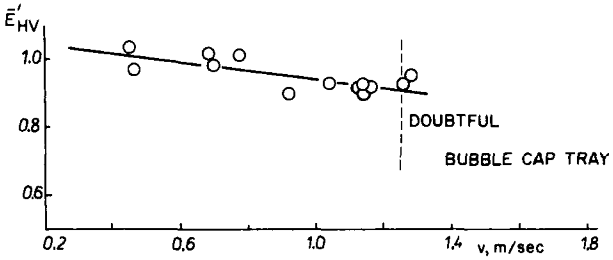
The values of the reduced generalized Hausen plate efficiency are shown on Fig. 16 for these same trays. It is easy to show that this efficiency is higher than either reduced Murphree tray efficiency, but the general dependence on vapor velocity can be seen to be similar to that of the latter vapor efficiency. We believe these values to be the first of this type to have been obtained experi-


1.2
$\bar{E}'_{HV}$
1.0
0.8
0.2
0.6
1.0
1.4
v, m/sec
1.8
UNIFLUX TRAY

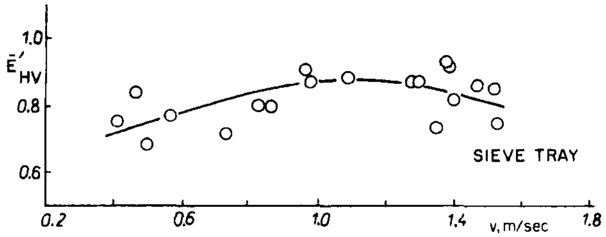
(a)


$\bar{E}'_{HV}$
1.0
0.8
0.6
0.2
0.6
1.0
1.4
v, m/sec
1.8
APV-WEST TRAY

(b)


$\bar{E}'_{HV}$
1.0
0.8
0.6
0.2
0.6
1.0
1.4
v, m/sec
1.8
DOUBTFUL
BUBBLE CAP TRAY

(c)


1.0
$\bar{E}'_{HV}$
0.8
0.6
0.2
0.6
1.0
1.4
v, m/sec
1.8
SIEVE TRAY

(d)

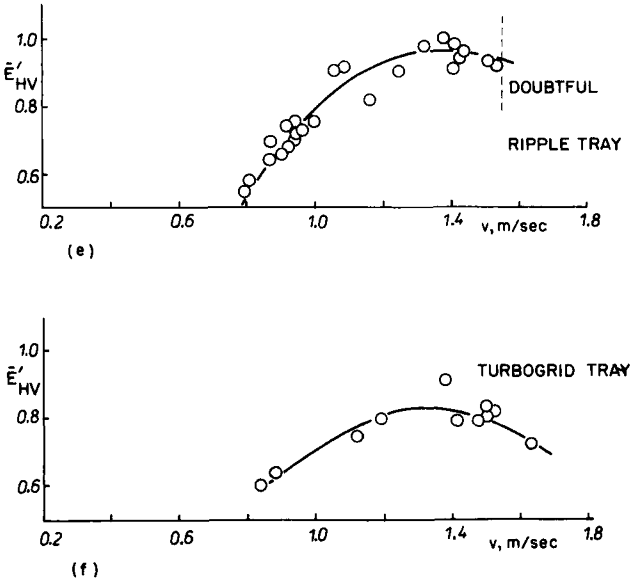


FIG. 16. Dependence of reduced generalized Hausen efficiencies on vapor velocity: (a) Uniflux tray; (b) APV-West tray; (c) bubble-cap tray; (d) sieve tray; (e) Ripple tray; (f) Turbogrid tray.

mentally either with or without the correction for entrainment. Further values will be presented in other papers of this series (*31,32*) for cases where the carryover in a much smaller column was negligible.

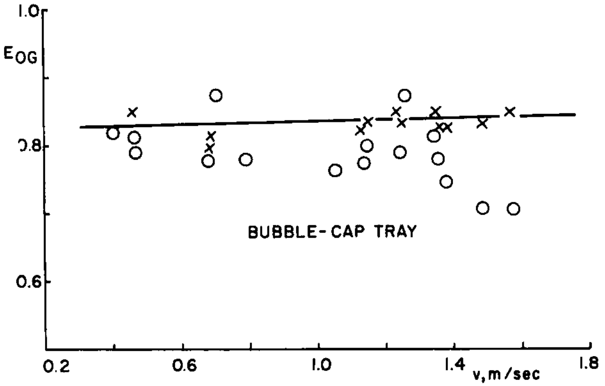
COMPARISON WITH PLATE EFFICIENCY CORRELATIONS

The Bakowski Correlation

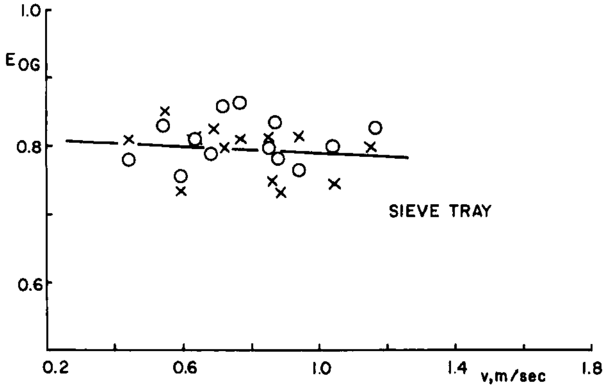
For bubble-cap trays Bakowski derived a relation for predicting local over-all conventional vapor efficiencies which has the form (*33*) (cgs units)

$$E_{OG}^{-1} = 1 + 3.7\,\frac{K\bar{M}}{h\rho_L T} \tag{6}$$

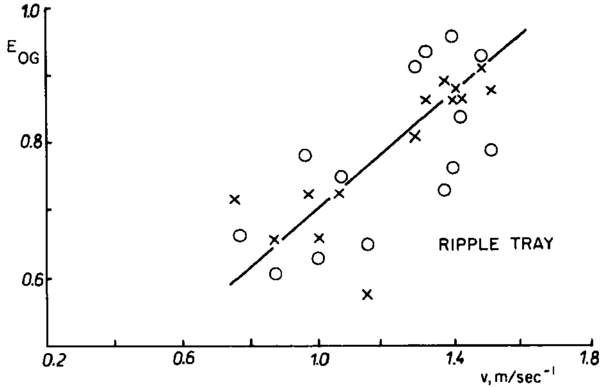
We criticized his derivation in (*28*) and do not consider it to be consistent; it is, however, possible to consider the final form as a semiempirical expression which involves a hydraulic parameter and several physical properties of the mixture being distilled.


1.0
E_{OG}
0.8
0.6
BUBBLE-CAP TRAY
0.2
0.6
1.0
1.4
v, m/sec
1.8

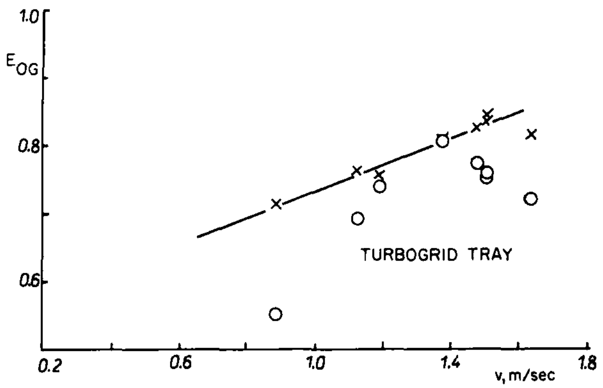
(a)


1.0
E_{OG}
0.8
0.6
SIEVE TRAY
0.2
0.6
1.0
1.4
v, m/sec
1.8

(b)


1.0
E_{OG}
0.8
0.6
RIPPLE TRAY
0.2
0.6
1.0
1.4
v, m/sec^{-1}
1.8

(c)



(d)

FIG. 17. Correlation of local over-all conventional vapor plate efficiencies according to Bakowski: O, experimental values; ×, curve according to Bakowski correlation. (a) Bubble-cap tray; (b) sieve tray; (c) Ripple tray; (d) Turbogrid tray.

We used this expression to try to correlate our experimental results for bubble-cap, sieve, Ripple, and Turbogrid trays. The hydraulic parameter *h* is not unequivocally defined by Bakowski [see the discussion in (*8*)], but our experience has shown that the most suitable interpretation of this parameter is as the height of clear liquid held up on the tray. We calculated this clear liquid height according to Rylek (*4*) for Ripple, Turbogrid, and bubble-cap trays, and, for sieve trays, according to Solomacha and Planovskij (*34*). The local over-all conventional efficiency was calculated according to (*28*). The deviations between the correlation and the experimental values for the bubble-cap (Fig. 17a), sieve (Fig. 17b), and Ripple (Fig. 17c) trays are not significant over the ranges where reliable stream samples could be obtained, so that this modified correlation can be provisionally recommended for the prediction of conventional plate efficiencies for these plates over the normal operating ranges. For the Turbogrid tray (Fig. 17d) the correlation is satisfactory only at the optimum operating point of maximum efficiency; otherwise it predicts too high efficiencies.

Kasatkin Correlation

Kasatkin et al. in a series of papers (*26,35–38*) propose a number of correlations for the mass-transfer coefficient per unit plate area

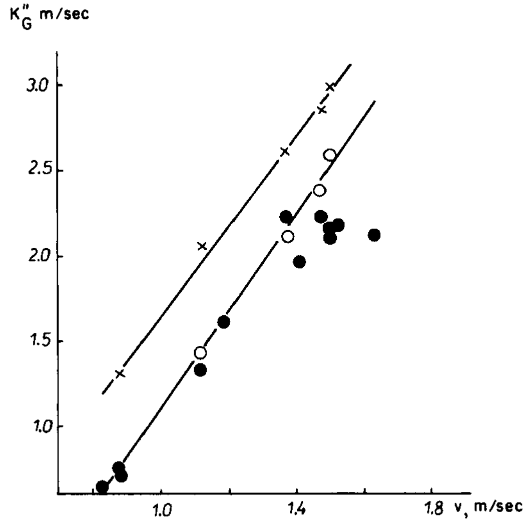


FIG. 18. Correlation of conventional vapor mass-transfer coefficient according to Kočergin and Huml: ●, experimental points; ×, curve according to Kočergin correlation; ○, curve according to Huml modification.

for an arbitrary tray, correlations that have the same form for each phase. One of the many variants they recommend has the form

$$Sh = 8.10^4 \times Pe^{0.5}\Gamma \qquad (7)$$

Regardless of certain theoretically incorrect assumptions of these authors (*28*), we tried to verify this correlation using our data on the Ripple tray, as this correlation is simple and contains hydraulic parameters, which we believe to be very important in efficiency studies. The agreement between the measured and predicted mass-transfer coefficients was not good, however, so the results will not be presented in detail.

Kočergin Correlation

For the methanol–water system Huml (*6*) used the same form of correlation equations for the individual mass transfer coefficients as was proposed by Kočergin (*18*). For the vapor phase Huml modified the original values of the coefficient and exponent in the Kočergin relation

$$Sh_G = ARe^n Sc_G^{0.25} \qquad (8)$$

to the values $A = 0.0019$ and $n = 2.08$ for a Turbogrid tray with a free area of 14–18%. He used the original form of the liquid-phase correlation

$$\mathrm{Sh}_L = 17\mathrm{We}^{0.15}\mathrm{Sc}_L^{0.5}\mathrm{Ga}^{0.7} \tag{9}$$

without change. We tested these relations for our Turbogrid tray ($\phi = 0.147$, slot width 4.5 mm) using the original Kočergin and the modified Huml correlations (see Fig. 18). The Kočergin relation predicts much too large values of the over-all mass-transfer coefficient, but the Huml correlation agrees well with our results at the lower vapor velocities. As stated earlier, however, our data are for a relatively narrow range of vapor velocities.

A.I.Ch.E. Correlation

The correlations proposed in the A.I.Ch.E. program (*20*) are empirical, dimensional relations which are intended to be easily applicable in practical calculations. They are purely interpolation formulas, and it is somewhat surprising that the data were not correlated in terms of dimensionless relations, as is customary when presenting extensive experimental results. We (*28*), as well as others [e.g., (*39*)], have presented discussions and criticisms of the A.I.Ch.E. procedures and results.

We compared our data for bubble-cap trays with the correlations presented in (*20*), and the results are shown on Fig. 19. The predicted values of the local conventional vapor efficiency are lower than the experimental ones, even though we have not considered

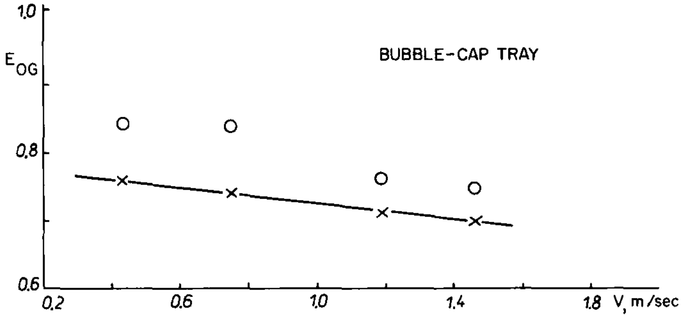


FIG. 19. Correlation of local over-all conventional vapor plate efficiencies for bubble-cap tray according to the A.I.Ch.E. method: ○, experimental points; ×, curve according to A.I.Ch.E. correlation.

the effect of carryover, which would tend to increase this difference. If we consider that for the lower vapor velocities the effect of carryover is still negligible, we may say that the absolute difference in the measured and predicted efficiency is about 10%. While this accuracy would be perhaps acceptable for design calculations for bubble-cap trays, it cannot be considered the final solution to the problem of predicting tray efficiencies even for this type of plate.

Planovskij Correlation

Planovskij et al. (*40*), as well as other Soviet authors, have presented an interesting interpretation of plate efficiencies wherein the conventional over-all mass-transfer coefficient is related to essentially the energy dissipated in maintaining the foam, which, as we have shown (*41*), is approximately $v\Delta p_p$. We can thus plot, say

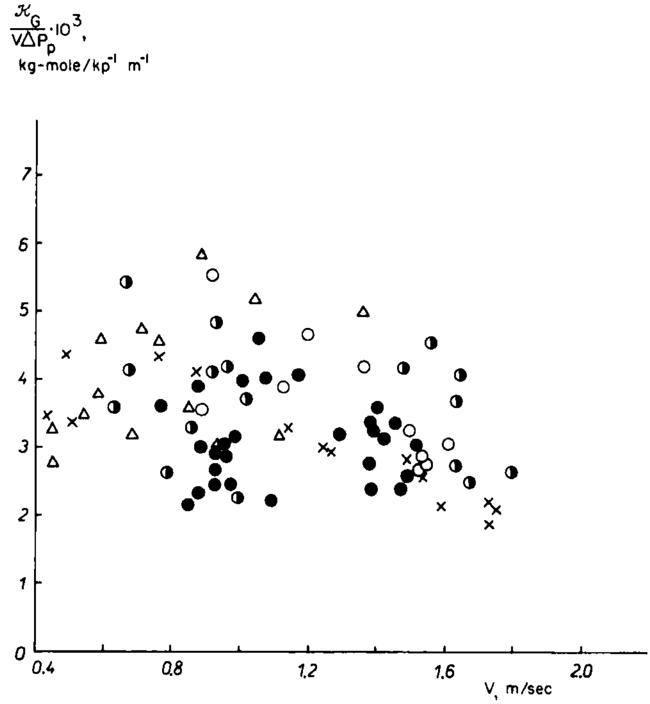


FIG. 20. Correlation of conventional over-all vapor mass-transfer coefficients according to Planovskij et al.: ●, Ripple tray; ◐, Uniflux tray; ○, Turbogrid tray; ×, bubble-cap tray; △, sieve tray.

$\mathscr{K}''_G/v\Delta p_p$, against, for example, the vapor velocity as shown on Fig. 20, for Ripple, Uniflux, Turbogrid, sieve, and bubble-cap trays. While the individual trays show slightly different trends, the scatter of the experimental points for each tray is larger than these differences, and the general agreement is remarkable in view of the simplicity and directness of the conception. We believe that this approach is well worth following up and refining.

CONCLUSION

In agreement with the original developments and derivations, these correlations were compared with the experimental values of the conventional Murphree or local vapor-plate efficiencies or the corresponding mass-transfer coefficients using the usual simple models of plate action. Even in cases where the entrainment was negligible, the agreement was, as in other confrontations of these correlations with experimental data, only fair to good. We believe, however, that in addition to the sampling errors discussed in this article and the errors in vapor-liquid equilibrium data which also directly influence the values of plate efficiencies and transfer coefficients, it is necessary to take account of entrainment when making such correlations not only in the definitions of the plate efficiencies themselves but also in the models of plate action by means of which we calculate local efficiencies (assuming we employ them at all) and, in general, the transfer coefficients. Finally, the correlations of these variables in dependence on the operating conditions of the plate, etc., should also take entrainment into account. We intend to consider these questions later, as much work, both experimental and theoretical, must be done before we may consider that we have reliable methods for predicting plate efficiencies of individual plates and still more of general models of trays.

APPENDIX: PLATE CHARACTERISTICS

Internal cross section of columns	0.747 m^2
Plate spacing	0.4 m
1. Bubble-cap plate:	
Length of outlet weir (chord type)	0.68 m
Height of outlet weir	0.060 m
Distance between downcomers	0.68 m

Bubble caps:	
Caps on equilateral triangular layout with pitch	105 mm
Number of caps on plate	49
Number of rows of caps parallel to weirs	6
External height of cap	69 mm
Internal height of cap	67.5 mm
External diameter of cap	70 mm
Internal diameter of cap	66 mm
External diameter of riser	49 mm
Internal diameter of riser	44 mm
Height of riser	63 mm
Number of slots in cap skirt	19
Size of rectangular slots	30 × 5.5 mm
Skirt clearance	7 mm
Relative free area of risers	0.100
2. Sieve plate:	
Length of outlet weir (chord type)	0.612 m
Height of outlet weir	0.040 m
Distance between downcomers	0.759 m
Holes on equilateral triangular layout with pitch	15 mm
Number of holes on plate	2499
Diameter of hole	4 mm
Relative free area of holes	0.042
3. Uniflux plate:	
Length of outlet weir (chord type)	0.676 m
Height of outlet weir	0.070 m
Number of S segments on plate	4
Dimensions of S segments	see Fig. 21
Relative free area of riser slots	0.146
4. APV-West plate:	
Over-all layout	see Fig. 22
Height of outlet weir	0.045 m
Mean length of one "cap"	0.73 m
Internal width of riser	35 mm
External width of cap	75 mm
Clearance between riser and cap	11 mm
Clearance of cap above plate	16.5 mm
Distance from plate to top of perforated plate	21 mm

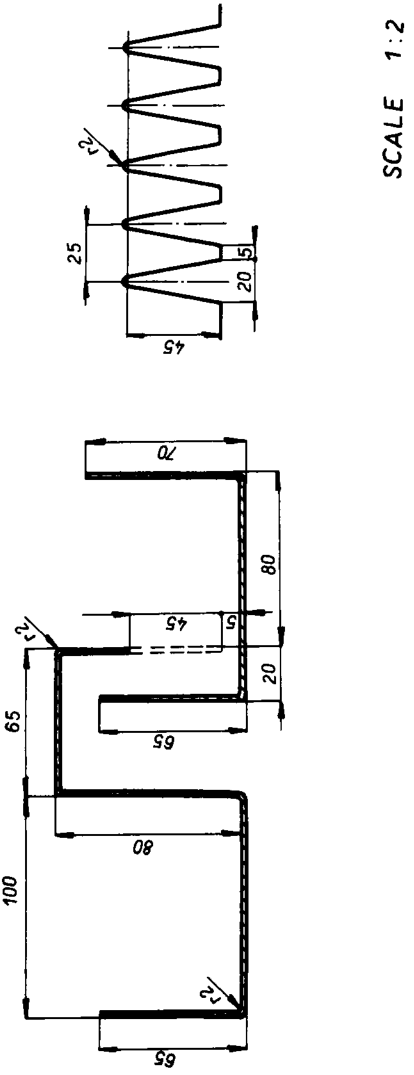


FIG. 21. Uniflux-tray S-segment detail; all dimensions in millimeters.

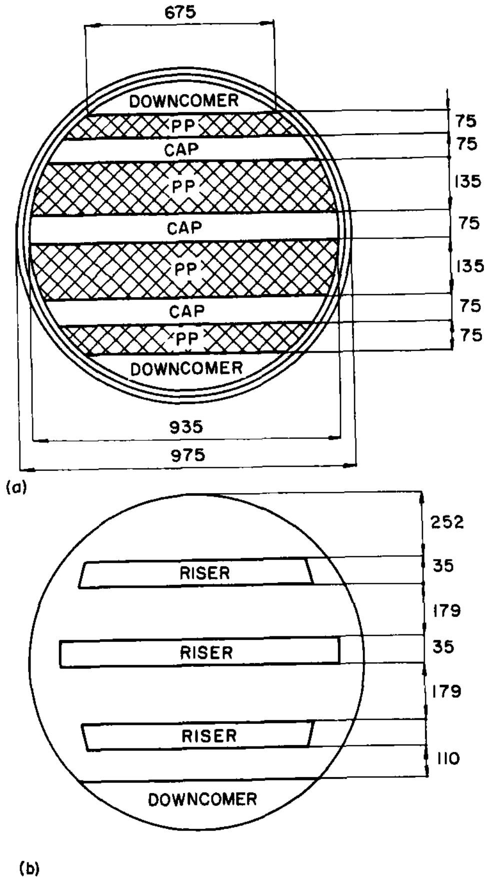


FIG. 22. APV-West tray, general layout; all dimensions in millimeters: (a) upper part of tray (PP, perforated plate section); (b) lower part of tray.

Holes in perforated plate on equilateral triangular layout with pitch	13 mm
Number of holes per 100 cm^2 of perforated plate	68
Diameter of holes in perforated plate	8 mm
Relative free area of riser slots	0.107
5. Ripple plate:	
Wavelength of plate ripple	50 mm
Height (amplitude) of plate ripple	12.5 mm
Holes on equilateral triangle layout with pitch	9 mm

Number of holes per 100 cm^2 of plate	199
Hole diameter (original)	3 mm
Hole diameter after bending plate (av)	2.85 mm
Relative free area of holes	0.108
6. Turbogrid tray:	
Uninterrupted slot average width	4.5 mm
Relative free area of slots	0.147
Plate thickness	4 mm

List of Symbols

A	constant [Eq. (18)]
D	diffusivity
e	porosity of foam (for vapor)
$e^{+\prime}$	reduced relative liquid carryover [see Eq. (VIII-17)]
$e^{-\prime}$	reduced relative liquid weeping [see Eq. (2)]
E_{OG}	local conventional over-all vapor plate efficiency
E	conventional plate efficiency [e.g., Eq. (5)]
$\bar{E}$	apparent plate efficiency [e.g., Eq. (4)]
$\bar{E}'$	reduced plate efficiency [e.g., Eq. (3)]
$\dot{E}_n^{-\prime\prime}$	liquid molal weeping rate from *n*th tray [see Eq. (VIII-4)]
F	$\equiv v\rho_G{}^{1/2}$, F factor
Ga_L	$\equiv h^3g/\nu_L^2$, Galileo number
h	clear liquid height
ΔH	free height above foam
k	partial mass-transfer coefficient of stream
K	$\equiv y/x$, equilibrium ratio
$\mathcal{K}$	over-all mass-transfer coefficient per unit active plate area and mole fraction difference
$\mathcal{K}''$	over-all mass-transfer coefficient per unit active plate area and molar concentration difference
l	general length [$l = 1$ in Eq. (7)]
$\bar{M}$	mean molecular weight of mixture
n	exponent [Eq. (8)]
Pe	$\equiv vl/eD_G$ or $wl/(1-e)D_L$, Peclet number for vapor or liquid
Δp	pressure drop across tray
Δp_h	pressure drop corresponding to liquid holdup
Δp_p	$\equiv \Delta p_h + \Delta p_\sigma$, pressure drop across foam
Δp_σ	pressure drop due to surface tension
Re	$\equiv \rho l v/\mu$, Reynolds number
R'	reduced reflux ratio [see Eq. (VIII-16)]

Sc	$\equiv \mu/\rho D$, Schmidt number
Sh	$\equiv Kl/D$, Sherwood number [$\mathrm{Sh}_G \equiv k_G l/D_G \rho$ in Eq. (7)]
T	absolute temperature
v	vapor (gas) velocity in column free cross section
$\dot{V}'_n$	reduced vapor molal flow rate from *n*th tray [see Eq. (VIII-7a)]
We	$\equiv v^2 \rho l/g\sigma$, Weber number
$\bar{x}$	actual liquid mole fraction
$\bar{x}'$	reduced liquid mole fraction [see Eq. (VIII-9)]
$\bar{y}$	actual vapor mole fraction
$\bar{y}'$	reduced vapor mole fraction [see Eq. (VIII-9)]
$(\bar{y})$	conventional vapor mole fraction
γ	specific weight of phase
Γ	$\equiv \Delta p_h/\gamma_L l$
μ	viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
φ	relative plate free area

Indices

D	distillate
G	gas (or vapor)
H	Hausen
L	liquid
M	Murphree
n	plate number
V	vapor (or gas)
x	liquid
$\underline{y}$	vapor
	actual value (mean over cross section)
′	reduced value
( )	conventional value
*	equilibrium value

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