Improving Hydraulics and Efficiencies with the T-By Sieve Tray

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A modified sieve (that is, T-By) tray uses a system of weirs and risers to approximate liquid plug flow over a cross-flow, circular-section tray. Vapor-liquid contact is improved using a system of curtain-pattern vapor holes and intermediate weirs to form cells across the tray that promote liquid mixing into discrete, well-mixed pools and stabilize froth. A theoretical model is used to analyze experimental data, guide tray design, and suggest new strategies for improving performance. These results indicate that tray efficiencies and stabilities can be increased without capacity losses. Pressure drop can also be manipulated to enhance performance.

Introduction

The cross-flow, circular-section sieve tray is used widely for vapor-liquid contacting in distillation towers. It promotes mass transfer by providing intimate contact between the two phases. The transport rates are generally proportional to the interfacial area, but the liquid-phase boundary layer and transport into the bulk phase can also be important. It is desirable to promote turbulent mixing and minimize resistance to mass transfer, but turbulence also causes backmixing and increases eddy diffusivity which decrease overall tray efficiency.

Fluid mechanics play an important role in efficiency and other key tray properties such as capacity and turndown ratios. However, the complexity of hydraulic behavior has led to design procedures which are largely empirical, even though the features of the basic sieve tray are quite simple.

Tray efficiency has been reviewed by many investigators (Geddes, 1946; Gerster, 1963; Fair, 1984; Lockett, 1986). Attempts at fundamental modeling were begun by Geddes (1946) and have been followed by others (Hughmark, 1971; Burgess and Calderbank, 1975; Stichlmair, 1978; Neuberg and Chuang, 1982; Zuiderweg, 1982). More recently, Prado and Fair (1990) have attempted to relate the regime type to the mass-transfer efficiency. Factors affecting sieve tray hydraulics (such as jet and bubble formation, bubble sizes and rise velocities, and average void fractions) were combined with diffusional models to predict mass transfer on an active sieve tray.

Liquid maldistribution also plays an important role in tray efficiency. Its effects have been widely reported (Strand, 1963; Zuiderweg et al., 1969; Bell, 1972; Weiler et al., 1973; Stichlmair and Weisshuhn, 1973; Stichlmair and Ulbrick, 1987; Lockett and Safekourdi, 1976; Neuberg and Chuang, 1982) and studied using a variety of models (Porter et al., 1972; Nuberg and Chuang, 1982; Solari et al., 1982).

Laminar flow of a Newtonian fluid in a horizontal pipe or rectangular tray leads to a parabolic velocity profile. Liquid entering a rectangular tray at its center, therefore, is expected to have a greater axial velocity than fluid elements traveling closer to the side baffles or column walls. This effect becomes more significant as the tray length (and diameter) increase, because the flow becomes more fully developed.

Circular-section, single-pass trays experience additional maldistribution effects due to stagnant regions. These effects increase with column diameter, and flow control becomes increasingly important in larger diameter columns. Various schemes have been used to address this problem. Smith and Delnicki (1975), for example, proposed slots in the tray deck to compensate for liquid maldistribution.

Conventional sieve tray design further exacerbates liquid channeling because the trays are circular. In essence, the average fluid velocity near the center of the tray is less than the average velocity downstream of the inlet weir or upstream of the overflow weir. The net effect, especially as tray diameters increase, is to increase the effective difference in fluid velocity between the center of the tray and the edges. This factor becomes significant for towers over 2 m in diameter (Bennett and Grimm, 1991). Yu et al. (1990), for example, present measurements of mean residence time profiles using tracer techniques on single- and double-pass half-trays. Their results clearly show that circular-section trays increase the velocity gradient and eddy diffusivity. They suggest that backmixing and stagnant zones occur in larger-diameter trays near the edges. Equivalently, the liquid on the interior of the tray "channels," because that is where the largest fluid velocities occur.

In principle, rectangular trays reduce the stagnant zones in sieve trays. This design option has been studied by several investigators (Finch and Van Winkle, 1964; Kalbassi et al., 1987). The AIChE project applied a one-dimensional eddy diffusivity model to a tray with rectangular cross section (AIChE, 1958). Yu et al. (1990) extended this model to two-dimensional flow and consider diffusion coefficients in the longitudinal (main flow) and transverse (perpendicular to main flow) directions. They conclude that liquid profiles, even on a single-pass sieve tray, are complex. There is a central zone of nonuniform flow with a parabolic velocity distribution. There is also a segmental zone of slow forward or backward flow with possible fluid circulation.

The hydraulic and efficiency behavior of sieve trays virtually defy rational explanation. There can be frequency effects, for example, which appear as frothy oscillations during operation and may result in resonance behavior. The liquid-phase flow patterns are difficult to idealize. A more realistic evaluation includes an analysis of droplet trajectories, which results in a further complication (Bennett and Grimm, 1991), but clearly is an important factor in backmixing.

Modifications to conventional sieve trays must be simple and straightforward to have practical value. They can be justified only by better liquid and vapor contact, greater efficiencies, and stabler operation. Modifications which produce a more uniform and stable froth, while reducing liquid maldistribution and ineffective vapor work, can reasonably be expected to contribute positively toward achieving these goals. Our approach and results are described below.

Pressure Drop and Efficiency

Pressure drop and tray efficiency are correlated, but it may be possible to partially decouple them. We hypothesize that tray pressure drop is partly used beneficially to increase efficiency, but that part is also wasted through random liquid droplet motions that do little to improve vapor-liquid contact.

The total wet pressure drop h_{wt} is conveniently divided into several terms (Lockett, 1986):

$$h_{wt} = h_{dt} + h_{cl} + h_r \tag{1}$$

When considering tray efficiency, it is useful to define a net-wet pressure drop h_{nw} as:

$$h_{nw} = h_{wt} - h_{dt} = h_{cl} + h_r \tag{2}$$

where the dry tray pressure drop h_{dt} is easily measured as a function of gas velocity through a tray and then subtracted from the total wet pressure drop h_{wt}. Consistent with our hypothesis, we consider part of the net-wet pressure drop to be *effective* in promoting mass transfer and part to be *ineffective*.

Lockett (1986) discusses models for clear liquid pressure drop h_{cl} and residual pressure drop h_r in some detail. Taken together, they equal the net-wet pressure drop and include several effects (such as surface tension forces, liquid head, and kinetic energy and frictional losses).

Certain generalities remain valid for any distillation tray design and are the motivating factors underlying our modifications. First, mass-transfer efficiency is generally proportional to the effective net-wet pressure drop across a tray, and energy should be used effectively to create new liquid surface area, mix fluids, increase contact time, and decrease boundary layer resistance. On the other hand, ineffective net-wet pressure drop and fluid energy are wasted through frictional losses and random liquid displacements that do not enhance mixing and mass transfer. These losses, however, can be reduced by designing the tray to exploit natural fluid circulation patterns and, thereby, conserving rotational fluid momentum.

Second, tray configurations that increase froth stability also increase the effective net-wet pressure drop and mass transfer. Hydraulic stability, therefore, is a primary design goal. It is increased through intermediate weirs that partially dam and stabilize liquid flow across the tray.

Third, modifications that reduce the transverse velocity gradient also improve efficiency. Ideally, liquids should cross a tray with plug flow. Our strategy is a compromise that reduces transverse gradients and increases local mixing so that plug flow is approximated more nearly.

Fourth, liquid and froth flow patterns should be controlled to decrease vapor work. Thus, we deliberately induce rotational liquid flow using a series of mixing cells. Vapor work is reduced by conserving froth rotational momentum in each cell. This rotational momentum also increases vapor entrainment, decreases froth density, and reduces frictional losses from less-productive random liquid movement.

Tray Description

Our modified sieve tray uses a system of intermediate weirs, risers, and curtain-pattern vapor holes to set up a series of multiple vapor-liquid contacting cells on each tray. Figure 1 is a plan view of the tray illustrating the active area A_b, downcomer area A_d, and stagnant (or inactive) areas A_s on each tray. The active bubble area A_b is given by:

$$A_b = A_t - 2A_s - 2A_d \tag{3}$$

where A_t is the total cross-sectional area of the column. The net vapor cross-sectional area A_n is reduced by the area of one downcomer, but not by A_s, as suggested by Figure 2. Thus,

$$A_n = A_t - A_d \tag{4}$$

is used to compute the flooding velocity as with conventional sieve trays.

This tray layout increases the hole to active area ratio A_f ($A_f = A_h/A_b$), which is used to estimate the Souders-Brown capacity factor. This increase results from the reduction in A_b,

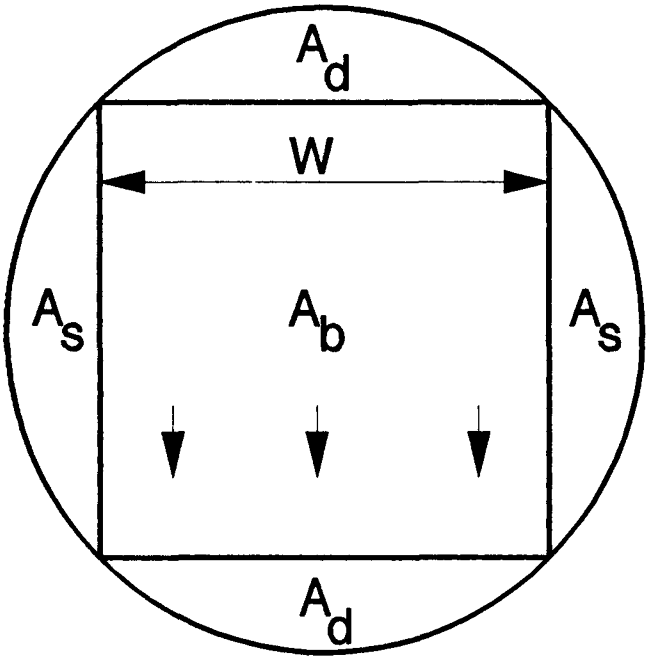

Figure 1. Plan view of a T-By sieve tray indicating the active A_b, stagnant A_s, and downcomer A_d areas.

compared to conventional sieve trays (Henley and Seader, 1981).

Figure 2 is a perspective view illustrating the general features of a T-By tray as patented by Parker and Parker (1988). Label 26 shows a single row of curtain-pattern vapor holes extending

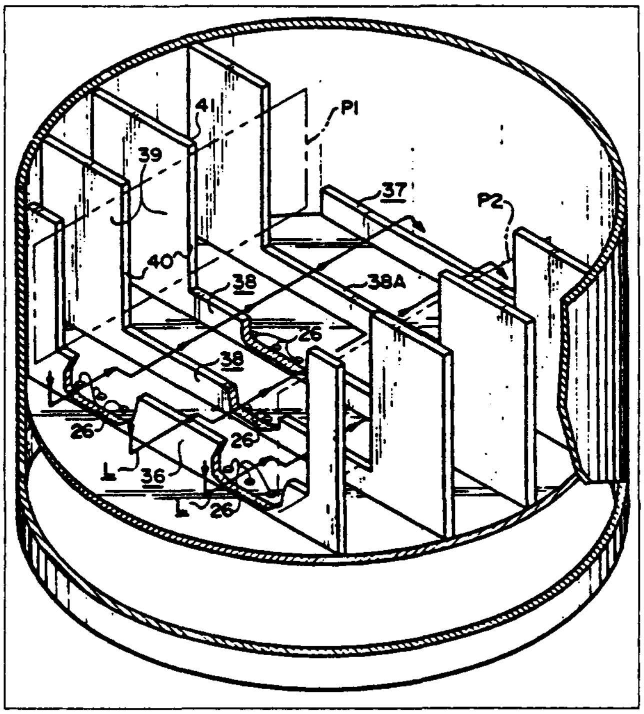

Figure 2. Perspective view of a T-By sieve tray.

The side risers (39 and 41) and T-By weirs (38) decrease liquid maldistribution. The curtain pattern vapor holes (26) promote liquid circulation between the intermediate weirs, and multiple contacting between rising vapors and cross-flowing liquids.

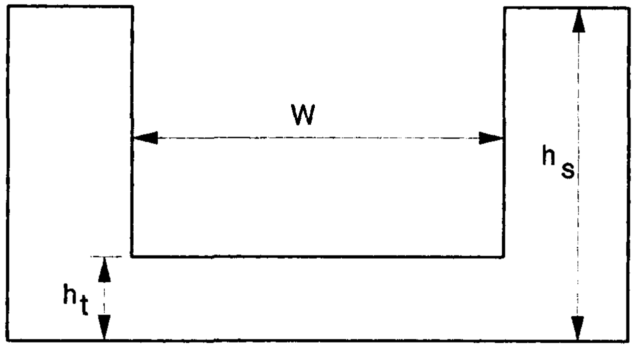

Figure 3. Key dimensions associated with the intermediate weirs and side risers (front view).

between planes P1 and P2 in Figure 2. The active contacting area, A_b, extends between planes P1 and P2, the inlet weir 36 and the overflow weir 37. Label 38 indicates the intermediate weirs that partition the tray into cells and stabilize liquid movement. Labels 39 and 41 indicate the risers that partition the stagnant (or inactive) area A_s on either side of the active mass transfer zone A_b.

In principle, these modifications have only a minimal effect on vapor velocity, because A_n is not reduced compared to a conventional sieve tray. The tortuosity of the vapor flow, however, is increased, since it must diverge over A_s and then converge to pass through the holes in A_n for the next tray.

Side baffles (such as planes P1 and P2 in Figure 2) have been studied by many investigators as a means to reduce backmixing and provide more uniform liquid flow across the tray. The T-By tray uses side risers (39 and 41 in Figure 2) to approximate the same benefit without reducing A_n, the net area for vapor flow. Several key dimensions of these intermediate weirs and side risers are illustrated in Figure 3. The liquid overflow width W is the same as the inlet and overflow weirs. The side riser height h_s determines the height to which froth must rise to bypass an intermediate weir.

The depth of each cell is partly set by the height of the intermediate weir h_t and partly by the heights of the inlet and overflow weirs, h_{in} and h_{ow}, respectively, as indicated in Figure 4. The width of each cell is w_t. It affects the circulation velocity within each cell as does the hole diameter d_h, the area percentage of holes A_h, and the curtain-pattern vapor holes in each cell. All tests thus far have been conducted using curtain

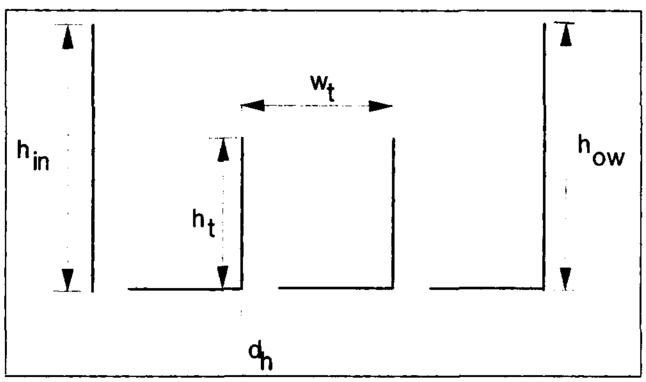

Figure 4. Key dimensions associated with T-By cells (end view).

patterns that cover 50% of w_t or less. In all cases, the curtain-pattern holes only extend over the active area of the tray (width W in Figure 3).

The intermediate weirs and curtain-pattern vapor holes are intended to provide four benefits: (1) more uniform froth height across a tray; (2) more stable froth and liquid movement across a tray; (3) reduced liquid maldistribution across a tray; and (4) improved liquid and vapor mixing within each cell. The first two benefits are relatively straightforward and, in fact, have been noted in virtually all of our tests. The last two are more subtle and are discussed in more detail below.

Liquid maldistribution

Liquid crossing a sieve tray is elevated to a highly turbulent froth by vapor sparging and the average liquid velocity across the tray. In a conventional tray, concentration gradients result from velocity differences across the tray and mass transfer in the transverse direction due to backmixing in the stagnant side-regions A_s. Lockett (1986) discusses liquid flow maldistribution in some detail. Porter et al. (1972) provide theoretical concentration profiles based on the stagnant regions model (SRM). Bell (1972) provides experimental measurements of this effect.

The side baffles (as in P1 and P2 in Figure 2) reduce the concentration gradients by eliminating the stagnant areas altogether, as already noted. This approach also reduces A_n and decreases column capacity. In a similar fashion, the side risers in the T-By tray (see Figures 2 and 3) attempt to approximate the benefit of side baffles, but without reducing A_n. Since there are no vapor holes in areas A_s of a T-By tray, all mixing in these zones results from liquid recirculation. Ultimately, liquid is forced through the active zone and over the next intermediate weir through the width W in Figure 3. Thus, diverging and converging liquid flow patterns are reduced as liquid flows between cells, but not within a cell where liquid may still recirculate between the active and stagnant zones.

The effect of the intermediate weirs in reducing liquid maldistribution can be understood by considering Figure 5, which depicts an end view of three cells, similar to Figure 4. Liquid is forced over an intermediate weir with average velocity V_L. Because the liquid depth over the weir is less than the depth in the preceding cell or downcomer area by h_t, relative horizontal velocity in the cell and over the weir is given by:

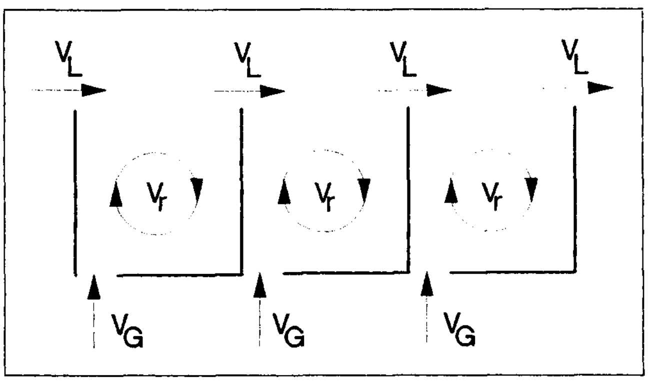

Figure 5. Liquid is accelerated to V_L by crossing over each intermediate weir (end view).

After crossing the weir, it decelerates and begins circulating with average velocity V_r induced by the dimensions of the cell and the vapor velocity, V_g.

$$\frac{V_L}{V_c}=\frac{h_L}{h_L-h_t} \tag{5}$$

where h_L is the average, local froth depth. So the fluid acceleration across each intermediate weir increases with h_t and disrupts the development of transverse velocity gradients.

Because a parabolic velocity profile results from steady laminar flow, any process that rapidly accelerates and decelerates the fluid also disrupts this development. Such disruption clearly occurs as froth overflows each intermediate weir, even in the absence of cell circulation induced by the vapor flow V_g as discussed below.

This observation also suggests that the intermediate weir spacing affects the degree to which the liquid profile overflowing the stage approximates plug flow. An approximate estimate for spacing requirements and their effects can be obtained by considering unsteady laminary flow in circular tubes. Szymanski (1932) provides a solution which is discussed by Bird et al. (1960). For a fluid of constant ρ and μ, a constant pressure gradient imposed on the system leads to a solution based on zero-order Bessel functions. Imposition of the constraint that $v_z/v_{max}\leq 0.05$ for $0\leq r/R\leq 1.0$ and substitution of the cell dimensions for diameter leads to the approximation:

$$w_t\leq\frac{0.05}{\pi\nu}\left(\frac{D}{W}\right)Q_L \tag{6}$$

where $\nu=\mu/\rho$. This analysis suggests that even loosely spaced intermediate weirs will help maintain plug flow more nearly.

Cell mixing

Triangular- or square-pitch hole patterns are typically used in conventional sieve trays. This layout yields randomized mixing patterns and does little to enhance froth stability. In contrast, the vapor holes in our modified tray are arranged just downstream of each intermediate weir. The idea is to promote liquid circulation as illustrated in Figure 5.

There are several variables that either promote or hinder liquid circulation and gas contact in each cell. These include: (1) the hole diameter and pattern, (2) the width of the cell, and (3) the height of the intermediate weir and cell (also see Figure 4). In general, the dimensions should be set to maximize froth circulation $V_r=\omega r$ as illustrated in Figure 5. To do this, the cell layout must exploit the hydrodynamic behavior of gas-liquid mixtures.

Fluid circulation tendencies can be understood by considering analogies with air-lift pumps (Brown et al., 1990; Bennett and Myers, 1982), bubble columns (Joshi and Sharma, 1979; Joshi, 1980, 1982), and reattaching horizontal flow past rigid bodies (Narayanan and Reynolds, 1968). Lamb (1946) has analyzed the axisymmetric case and provides a stream function to describe the vorticity ω of an inviscid fluid.

Qualitatively, fluid circulation patterns are elongated in the direction of the circulating force as indicated in Figure 6. By analogy with air lift pumps or bubble columns, froth circulation is expected to elongate in the same direction as the vapor flow (Figure 6a). By analogy with reattaching flow past rigid bodies, froth circulation in a cell is expected to elongate in the same direction as the liquid flow over the intermediate weir (Figure 6b).

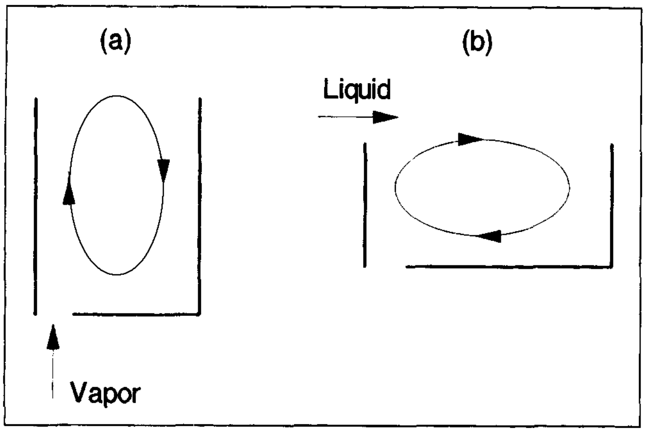

Figure 6. Flow patterns anticipated from (a) air lifts or bubble columns and (b) reattaching flow past a rigid body.

Narayanan and Reynolds (1968) discuss the basic ideas behind the pressure gradients in recirculating flow. Reattaching flow or eddying wakes occur in cases of uniform, continuous flow past a rigid body. In summary, the mean recirculation pattern for water flow is typically six times as long as it is wide. This effect suggests that the natural recirculation patterns in an intermediate weir should be as indicated in Figure 6b, rather than the distorted pattern, Figure 6a, that is anticipated for bubble columns with $V_L=0$.

Bubble column hydrodynamics and rotational wakes downstream of rigid bodies both have implications for the T-By cell and its design. Cell vorticity is clearly a function of the d_h/w_t ratio, hole layout in the cell, and the h_t/w_t ratio. Clearly the curtain-pattern vapor holes should not cover more than half of the cell width, since the fluid must rotate about a stationary point in each cell. In addition, the hole diameter affects bubble size and fluid displacement characteristics resulting in a steady-state ω. Thus, the d_h/w_t ratio must be considered when selecting d_h.

Second, the height and width of a cell should be proportional to promote vorticity. Based on Joshi's work with bubble columns, $1.6 \le h_t/w_t \le 2.0$ will give the best performance, while Narayana and Reynolds' work with reattaching flow indicates that, $0.17 \le h_t/w_t \le 0.2$ would be best. Thus, these two factors are in competition. In addition, Lamb's analysis is based on inviscid flow, and Joshi's observations are relevant primarily for low-viscosity fluids (that is, air-water mixtures). Petroleum fractions with viscosities and densities significantly different from water may circulate better in cells that have different sizes from those which maximize ω for air-water mixtures.

Intuitively, one may expect that circular flow patterns will provide the least resistance and maximize ω. This hypothesis suggests that h_t and w_t should be about equal. The considerations listed above, however, also suggest that the best ratio depends on V_g and V_L.

Using the dimensions in Figure 7 suggests the following boundary conditions to model the T-By cell:

$$v_x = V_L \quad \text{at} \quad x=0 \quad \text{and} \quad y=h_t+Q_L/WV_L \tag{7}$$

$$v_y = V_g \quad \text{at} \quad x=d_h/2 \quad \text{and} \quad y=0 \tag{8}$$

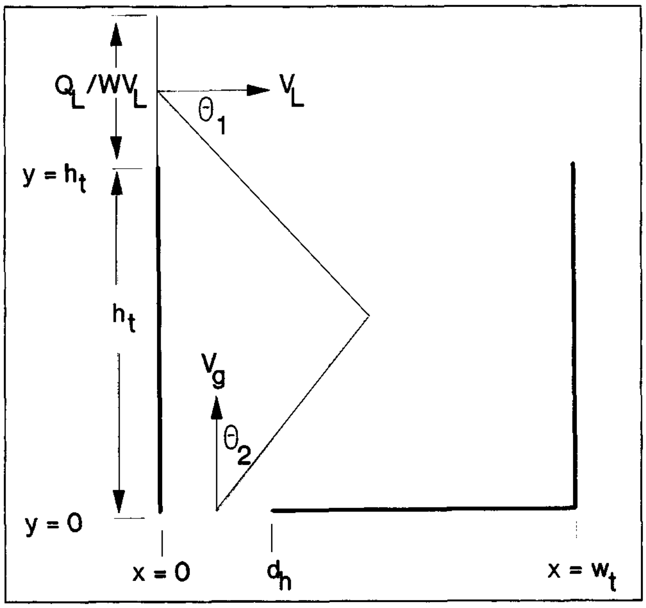

Figure 7. Flow patterns in a T-By cell.

In applying these boundary conditions to achieve circular (as opposed to oval) rotational flow, we require that the tangential velocity along each streamline be constant for all values of the angle θ around the centroid of each T-By cell vortex. Thus, from Figure 7, we obtain the momentum constraint:

$$\dot{m}_L V_L \sin\theta_1 = \dot{m}_g V_g \sin\theta_2 \tag{9}$$

where $\dot{m}_g = \rho_g Q_g (n_c/n)$ is the mass rate of vapor sparged into a cell over length W, and $\dot{m}_L = \rho_L Q_L$ is the liquid mass rate across a cell. Equation 9 leads to the relationship:

$$\frac{Q_L\rho_L n V_L}{Q_g\rho_g n_c V_g} = \left(\frac{w_t-d_h}{h_t+Q_L/WV_L}\right)\sqrt{\frac{(h_t+Q_L/WV_L)^2+w_t^2}{h_t^2+(w_t-d_h)^2}} \tag{10}$$

Equation 10 indicates that the best cell dimensions depend on the vapor and liquid flow ratio. At total reflux and with the additional imposed velocity constraint $V_L=(n_c/n)V_g$, Eq. 10 reduces to:

$$\frac{w_t}{h_t} = \frac{h_t+Q_L/WV_L}{w_t-d_h} \tag{11}$$

which is helpful in preliminary design. With an infinitely long intermediate weir and an infinitesimally small hole diameter, Eq. 11 reduces further to the expected result $w_t=h_t$.

Vapor work reduction

Maximizing vorticity in a cell can have two beneficial effects: (1) increased vapor entrainment and vapor-liquid contact times, and (2) reduced vapor work in passing through the tray. The first effect tends to increase mass transfer. The second tends to decrease *ineffective* net wet pressure drop across a tray.

Consider the flow patterns in Figure 5. Each T-By cell has a liquid circulation pattern with local rotational velocity $V_r=\omega r$. The kinetic energy of the rotating fluid in the cell is given by:

$$K_{tot}=\frac{1}{2}\int \rho_c V_r^2 dV \quad (12)$$

and the integral is evaluated over the cell volume. Writing the macroscopic mechanical energy balance around the liquid suggests that, at steady state, the froth work is simply the frictional losses ($\hat{W}=\hat{E}_v$). Writing the macroscopic mechanical energy balance around the vapor passing through the cell:

$$h_{wt}=\int \frac{dP}{\rho_c}=-\Delta\frac{1}{2}V_g^2-\Delta\hat{\phi}-\hat{W}-\hat{E}_v \quad (13)$$

which suggests that the pressure drop across the tray can be reduced, if the work $\hat{W}$ done by V_g in maintaining the liquid kinetic energy K_{tot} can be minimized. Frictional losses $\hat{E}_v$ are unavoidable, but conserving the liquid kinetic energy through rotational flow, rather than random motions as with a conventional sieve tray, offers the possibility of reducing the ineffective net-wet pressure drop without efficiency losses.

In a conventional sieve tray, local liquid velocities are random. Vapor sparging must provide energy to displace the liquid as well as overcome frictional losses. In a T-By cell, the froth vorticity should be maintained. In principle, the energy requirements for this maintenance can be reduced to approach $\hat{E}_v$ by proper selection of the cell dimensions.

Equation 12 depends on ρ_c, and this effective phase density is reduced by entrainment. Thus, the kinetic energy of the froth and the amount of work to maintain its kinetic energy are reduced to the extent that froth density is reduced by vorticity ω in the cell.

Several simple analogies help illustrate this point. For example, consider a beach ball trapped in the air stream generated by a small blower. This visual aid is often used in department stores or science exhibits. The ball reaches a steady-state height above the blower where it remains and rotates at a constant velocity, and one could measure the pressure drop from the mouth of the blower to a fixed height above the ball's location while the ball is in its steady-state position.

Now, compare the pressure drop to that which occurs during the transient when the ball is first dropped into the air stream at the mouth of the blower and allowed to reach its steady-state position. The pressure drop is greater during the transient, because the air stream must move the ball from the blower to its steady-state elevation, and it accelerates the ball until it achieves its steady-state angular momentum. Both the potential and kinetic energies of the ball are increased during this transient, and the pressure drop from the blower mouth to the same reference evaluation above it is greater than that when the ball is rotating at steady state.

Behavior in conventional and T-By trays are comparable to the beach ball. When correctly designed, the T-By tray conserves the liquid rotational momentum and makes it easier for the vapor to pass through the tray, similar to the ball rotating at steady state. In contrast, liquid motion in a conventional sieve tray is much more random, and liquid velocity is not conserved. Thus, performance in the latter tray is akin to the beach ball transient when it is placed into the air stream. Liquid droplets are randomly displaced by vertical translation, rather than rotated with constant angular momentum in a cell.

As a second illustration, the liquid kinetic energy in a conventional and T-By tray may be compared by the following argument. Consider a unit of liquid mass m in a conventional tray to be a rigid cube in a frictionless environment. As vapor passes through the tray, it must displace the cube and move it to height h_t before the vapor can escape around the liquid cube. Assume that the liquid cube is initially at rest over a vapor hole. The work done by the vapor is simply the change in kinetic and potential energies. In this case, $W=1/2mV_g^2+mgh_t$.

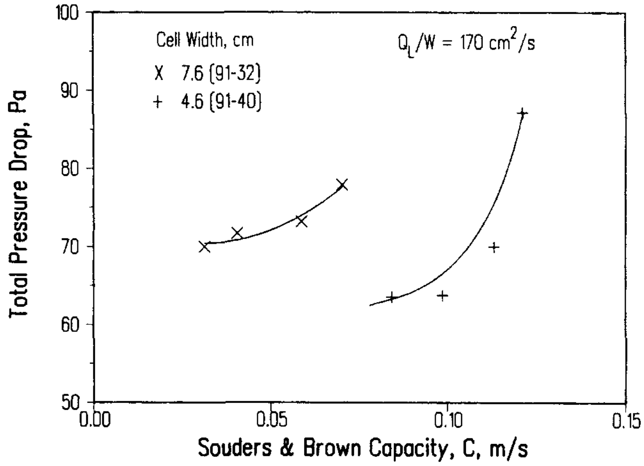

Figure 8. Total pressure drop across two comparable T-By cells with different cell widths.

In a T-By cell, the liquid is considered as a rigid, solid cylinder, rotating about a horizontal cylinder axis. Its rotational inertia is given by $I=1/2m(h_t/2)^2$, with kinetic energy $1/2I\omega^2$. The tangential velocity at $h_t/2$ is $V_g/\omega h_t/2$, and the kinetic energy of the rotating cylinder is $1/4mV_g^2$. Since the cylinder is rotating and not elevated by the gas passing it, there is no change in its potential energy and the gas work in passing through the tray (when the cylinder is initially at rest) is just the change in kinetic energy, and the net wet pressure drop would be less in passing the cylinder than that in moving a rigid cube of the same mass.

Such simple comparisons are obviously only qualitative, as vapor and liquid behaviors in sieve trays bear only slight resemblance to beach balls or rotating solids. We use these arguments to explain our concepts and our results, especially in those cases where the T-By tray appears to give lower net wet pressure drop than comparable sieve trays (Figure 8).

Experimental Methods

The experimental results presented here summarize findings from two types of measurements: (1) pressure drop across a tray and (2) E_o section mass-transfer efficiency. Conventional parameters (such as overflow and vapor velocities) were varied and compared with sieve tray performance. In addition, several T-By dimensions have been adjusted to find the best values for air and water mixtures.

Wet- and dry-pressure drops per tray have been measured at UNI-FRAC, Inc., Salt Lake City, the University of Texas at Austin, and at Glitsch, Inc., Dallas. Tray efficiencies have been measured at the University of Texas. Experimental methods for each site are summarized below.

UNI-FRAC, Inc.

Air flow was electronically measured with a Kurz Model

415-5 air velocity flowmeter. Water flow rates were measured using a Signet Scientific water flowmeter. The uncertainty in flow measurements was typically ±5%. The test column consisted of four trays at 0.46-m spacing per tray. Pressure drop was measured across the two interior trays and then averaged.

University of Texas

Section mass-transfer efficiencies were measured at three column pressures (0.33, 1.65 and 4.14 kPa) in a 0.46-m-diameter column that contained 14 trays at 0.46-m spacing per tray. The column was operated at total reflux and divided into two sections (above and below the feed tray). Section mass-transfer efficiencies and pressure drops were averaged across seven trays.

The column was operated at total reflux for 30 minutes or more before taking samples of the liquid phase from the edges of the bottom and top trays in a section of seven trays. All liquid samples were analyzed using gas chromatography with an internal standard. Reproducibility was about ±5% of each concentration measured. After taking the first set of samples, subsequent samples were taken at ten-minute intervals thereafter until steady state was achieved.

The column was controlled using a Fisher Porter Distributed Control System that controlled steam rates to the column as well as pressure (±0.7 Pa). Tests at 0.33 kPa were conducted using a vacuum pump controlled by the Fisher Porter system. The pressurized tests were conducted by the controlled addition of dry nitrogen to the column.

The hydrocarbon system was a mixture of cyclohexane and *n*-heptane. Theoretical trays and overall tray efficiencies were computed graphically using a McCabe-Thiele diagram. The operating line was based on vapor leaving the bottom tray of a section (either tray 7 or 14) based on the overall column energy balance and steam usage as estimated from the Fisher Porter Control System.

During startup, the column was initially flooded by using a high vapor rate until the trays were adequately sealed by liquid flow. Heat loads were then adjusted randomly to achieve the desired steady-state conditions. Reproducibility was established by duplicate runs from different starting points. The overall efficiencies were reproducible to within ±0.1%.

Two T-By tray configurations were studied simultaneously by placing seven trays with one configuration in the top section of the column and seven with the second in the bottom section.

Glitsch, Inc.

Three identical trays (either sieve or T-By) were stacked in a column. Pressure drop across the middle tray was measured using a Foxboro DP cell. A barometer was used to measure atmospheric pressure during each test. Thermocouples were used to measure wet- and dry-bulb temperatures at the top and bottom of the tower. A Foxboro flowmeter was used to measure the liquid rate; vapor rates were measured using a venturi meter.

Data were monitored continuously using a Hewlet Packard Electra 2100 computer to obtain a time series for each monitored variable. Pressure drop measurements across the middle tray for each set of conditions were made after five minutes or more of steady-state operation. Vapor velocities through the middle tray were computed using the measured variables and assuming ideal gas behavior. The pressure drop measurements were reproducible to ±2%.

The trays at all three sites were constructed using 0.46-m nominal tray spacing, but the side baffle heights were different. In particular, the side risers in the Glitch T-By tray extended to half of the full height between the trays. The T-By trays tested in Salt Lake City and at the University of Texas had side risers that were 7.62 cm high.

Table 1. Sieve Tray Diameters, Area Ratios, and Weir Heights*

Test No.	Diameters D, m	Diameters d_h, cm	A_h/A_t (%)	Weir Hts, cm h_{in}	Weir Hts, cm h_{ow}
92-59	0.46	0.64	10	5.08	1.91
92-58	0.46	0.64	10	5.08	2.54
92-57	0.46	0.64	10	5.08	5.08
92-56	0.46	0.64	10	5.08	7.62
92-64	0.46	0.64	8	5.08	1.91
92-63	0.46	0.64	8	5.08	2.54
92-62	0.46	0.64	8	5.08	5.08
92-61	0.46	0.64	8	5.08	7.62
GL-01	0.91	0.64	10	5.08	2.54
UT-01	0.43	0.48	9	0.00	5.08

*The tray spacing was 0.46 m, $W/D = 0.75$, and $A_n/A_t = 0.84$ for all.

Data Reduction

Gas flow rates were converted to the Souders and Brown capacity parameter:

$$C = \left(\frac{Q_g \rho_g}{A_n}\right) \frac{1}{[\rho_g(\rho_L - \rho_g)]^{0.5}} = \frac{Q_g}{A_n}\sqrt{\frac{\rho_g}{\rho_L - \rho_g}} \qquad (14)$$

Measured pressure drops and the absolute barometric pressure were used to adjust the air densities. Net-wet pressure drops were estimated by subtracting the measured dry pressure drop at ambient conditions, after adjusting the wet air density by the wet- and dry-bulb temperatures.

Vapor rates in the tests at the University of Texas were estimated from the column energy balances and expressed as mass rates using enthalpy data for the hydrocarbon system. Because the latent heats of vaporization for cyclohexane and *n*-heptane are nearly the same, this system yields nearly constant molar flow rates throughout the column when it is operated at total reflux.

Tray dimensions

Several tray dimensions were adjusted to measure the effects of layout on total and net-wet pressure drop, tray stability, flooding and weeping conditions, and mass-transfer efficiencies. Values for these dimensions are summarized in Tables 1 and 2 for sieve and T-By trays, respectively. Experimental results can be cross-referenced to the tray layout using the test numbers in these tables. The GL and UT series numbers reference tests were performed at Glitsch, Inc. and the Universiy of Texas, respectively. All other tests were performed in Salt Lake City.

Table 2. T-By Tray Diameters, Area Ratios, and Weir Heights*

Test No.	Diameters D, m	Diameters d_h, cm	A_h/A_t (%)	Weir Hts, cm h_{in}	Weir Hts, cm h_t	Weir Hts, cm h_{ow}	Weir Hts, cm h_s	Cell w_t, cm
91-26	0.46	0.64	10	2.54	1.91	1.91	10.2	6.99
91-27	0.46	0.64	10	2.54	1.91	1.91	10.2	6.99
91-31	0.46	0.64	10	2.54	1.91	1.91	15.2	7.62
91-32	0.46	0.64	10	2.54	2.54	2.54	15.2	7.62
91-39	0.46	0.64	10	2.54	1.91	1.91	15.2	4.60
91-40	0.46	0.64	10	2.54	2.54	2.54	15.2	4.60
91-47	0.46	0.64	8	2.54	1.91	1.91	15.2	6.99
91-48	0.46	0.64	8	2.54	2.54	2.54	15.2	6.99
91-49	0.46	0.64	8	2.54	5.08	5.08	15.2	6.99
91-50	0.46	0.64	8	5.08	2.54	2.54	15.2	6.99
91-51	0.46	0.64	8	5.08	2.54	2.54	10.2	10.16
91-52	0.46	0.64	8	5.08	2.54	2.54	10.2	10.16
91-53	0.46	0.64	8	5.08	2.54	2.54	15.2	4.60
GL-02	0.91	0.64	10	5.08	2.54	2.54	22.9	17.78
UT-11	0.46	0.61	6	5.08	1.91	1.91	15.2	6.99
UT-12	0.46	0.61	6	5.08	5.08	5.08	15.2	6.99

*The tray spacing was 0.46 m, $W/D=0.75$, and $A_n/A_t=0.84$ for all.

Results

These results have been synthesized from experimental measurements and observations at all three sites. The conditions described in Tables 1 and 2 are representative of our tests thus far, but not all inclusive. Our main observations are supported by figures using the experimental data, but several qualitative observations are presented without supporting data for the sake of brevity.

Inlet weir

Our pressure drop measurements and visual observations of fluid behavior show that an inlet weir is of critical importance for hydraulic stability, especially in smaller diameter trays. We observe that the quality and reproducibility of data measurements are much improved whenever an inlet weir is provided, and that the importance of this weir in tray desing is not widely appreciated.

An inlet weir is particularly helpful in eliminating vapor bypass through downcomers and enhancing tray stability. Improved hydraulic performance results for both conventional sieve and T-By trays whenever an inlet weir is provided, because it decreases vapor jetting and tray oscillations. The height of this weir h_{in} is not of great importance as long as the weir prevents vapor bypass.

Cell mixing and froth stability

All of our studies show that the intermediate weirs on T-By trays promote and stabilize froth compared to equivalent sieve trays. This effect is surprisingly large and even occurs in trays where the height of the overflow weir is greater than that of the intermediate weirs (for example, with h_t/h_{ow} ratios as low as 1/3).

The reasons for greater froth promotion and stability are most easily explained hydraulically. The intermediate weirs are essentially a series of small dams that force more uniform liquid heights throughout the tray. They also reduce liquid sloshing between the inlet and overflow weirs, and affect frequency response.

Since there is more room for liquid to slosh in larger diameter columns, the effect of these intermediate weirs on the promotion and stabilization of froth increases with tray diameter. The effects of h_t on froth are, in fact, much greater for larger-diameter trays than might be predicted from studies with smaller-diameter units.

The main benefit of a better quality froth is improved vapor-liquid contact. The potential disadvantages may be greater tendencies to flood at lower vapor rates and to exhibit higher net-wet pressure drops per tray. On the other hand, these disadvantages may be viewed as advantages if one wishes to design a tray with smaller overflow weirs, but similar behavior as a conventional sieve tray.

Our results suggest that the net-wet pressure drops per tray can be reduced by altering the froth circulation pattern. This change is achieved by adjusting the cell width and the curtain-pattern vapor holes. On the other hand, the intermediate weirs apparently stabilize froth whether their spacing (the value of w_t) induces froth circulation or not.

Froth vorticity is enhanced by restricting the hole pattern to 50% or less of the cell width w_t. Hole patterns that cover over 50% of the cell width destabilize circulation and increase the effective net-wet pressure drop. Similarly, there is little or no froth circulation when w_t is too large (Figure 9).

As expected from Eqs. 12 and 13, the cell width affects mixing and energy dissipation in the cell. Figure 8 illustrates results obtained for two different tray tests where all dimensions were identical, except for the cell width, w_t, which was either 4.6 or 7.6 cm.

As can be seen in Figure 8, the narrower cell appears to give lower pressure drops than the 7.6-cm cell, even at higher C values. This result suggests that the principle of conserving froth vorticity can be exploited in tray design. In this particular case, it appears that circulation was better in the 4.6-cm-wide cell as indicated by lower total pressure drops in Figure 8. This result is also consistent with Eq. 11 which suggests w_t should be about 3 to 4 cm.

Some of our observations at total reflux also suggest that froth circulation in cells can reduce the pressure drop to values below those for comparable sieve trays. Figures 9 and 10, for example, present pressure drop measurements across two sections of T-By trays and a section of sieve trays as measured

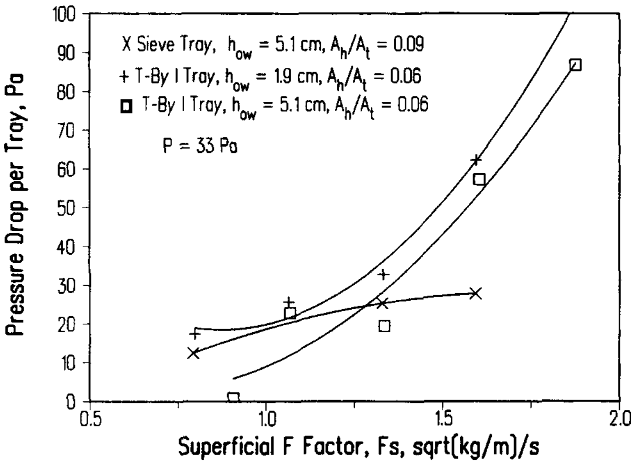

Figure 9. Total pressure drop per tray across two sections of T-By cells with different h_{ow} (UT-11 and UT-12) and a section of sieve trays (UT-01) at reduced pressure.

A_h was 30% greater for the sieve trays than the T-By trays.

at the University of Texas. As can be seen in both figures, the average pressure drop per tray was lower in the T-By than the sieve trays for three out of four tests at superficial F factors F_s less than 1.0 $(kg/m)^{0.5}/s$. One explanation for this result is cell circulation. It should also be recalled that Figures 9 and 10 underestimate the reduction in net-wet pressure drop by the T-By trays, as they were only 6% holes while the sieve tray was 9%. Because of this difference, the T-By trays should have higher total pressure drops except for the conservation of rotational momentum within the cells and the apparent reduction in vapor work through them.

In both Figures 9 and 10, the pressure drop per tray increases much faster for the T-By than the sieve trays. This result is due to the fact that the sieve trays did not have inlet weirs ($h_{in} = 0$ in Table 1), and vapor bypass occurred in them at higher values of F_s. These results support our earlier observation concerning the importance of inlet weirs.

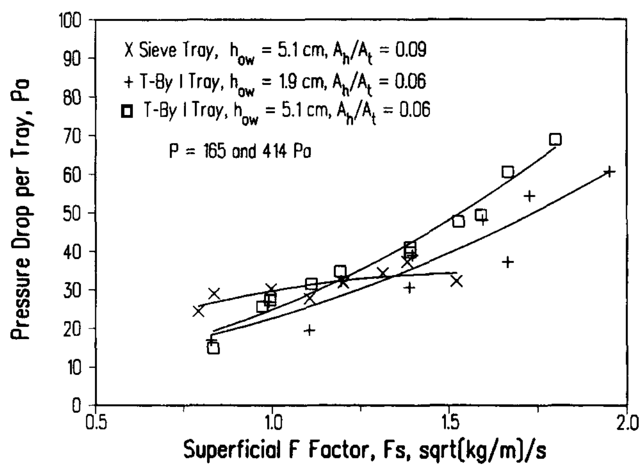

Figure 10. Total pressure drop per tray across two sections of T-By cells with different h_{ow} (UT-11 and UT-12) and a section of sieve trays (UT-01) at elevated pressures.

A_h was 30% greater for the sieve trays than the T-By trays.

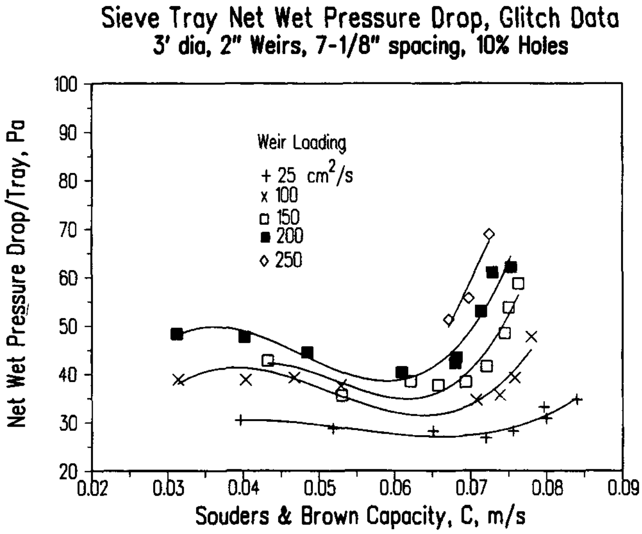

Figure 11. Sieve tray net-wet pressure drop from test GL-01.

Not all comparisons between T-By and sieve trays have resulted in lower net-wet pressure drops for the T-By trays. Measurements obtained by Glitsch are plotted in Figures 11 and 12. These results show higher pressure drops for the T-By tray tested in GL-02 than were obtained for the sieve tray tested in GL-01. It should be noted that the overflow and T-By weirs in the GL-02 tray were half h_{ow} in GL-01, the conventional sieve tray.

Even though the overflow weir in GL-02 was half that in the conventional sieve tray, the net-wet pressure drop was greater in the T-By tray over the entire operating range. The differences in net-wet pressure drop between these two trays are plotted in Figure 13 to further illustrate this point. As can be seen, the T-By tray has a higher net-wet pressure drop that increases steadily with the Souders and Brown Capacity, C.

The greater and more stable froth on GL-02 is the primary reason for the results in Figure 13. In this tray, however, h_t/w_t was less than 0.5, and liquid circulation was minimal

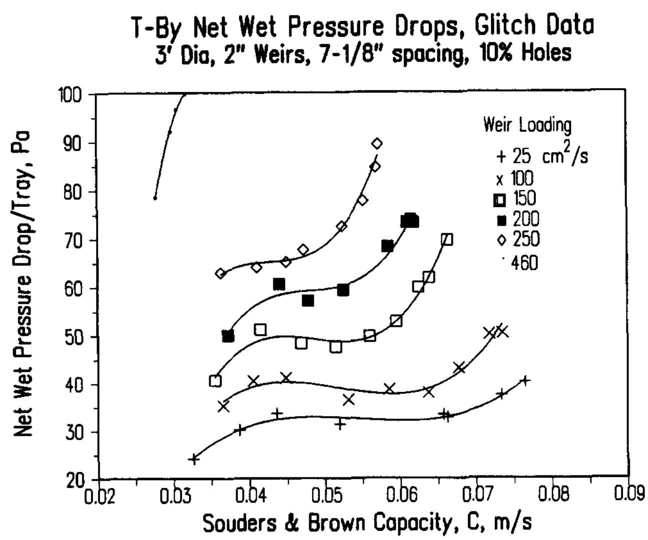

Figure 12. T-By tray net-wet pressure drops from test GL-02.

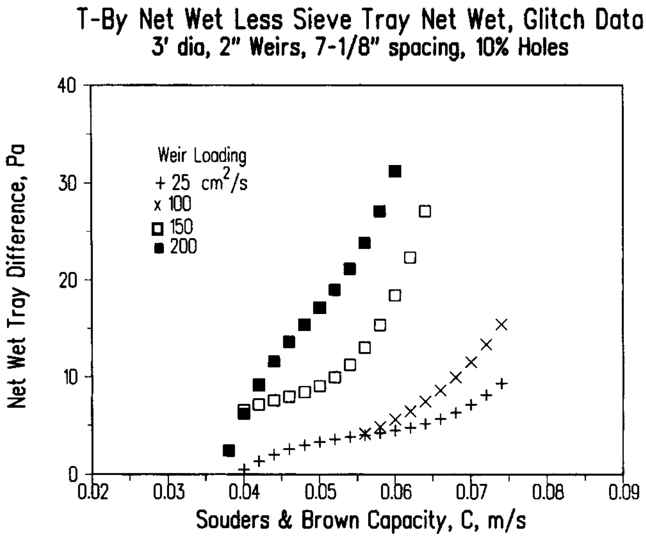

Figure 13. T-By net-wet pressure drop less the sieve tray net-wet pressure drop (GL-02 net-wet less GL-01 net-wet).

because w_t was 17.78 cm. This width was too large to promote liquid froth vorticity in the air-water system. Equation 11 suggests that a value for w_t in the range of 3 to 4 cm would have been more appropriate.

Figure 13 also indicates that intermediate weirs greatly stabilize froth even with excessively large values for w_t, consistent with the implications of Eq. 6. This effect results in larger net-wet pressure drops and reduced tray capacities, even with smaller overflow weir heights in the T-By tray.

Mass-transfer efficiency

Section efficiencies were measured at the University of Texas at three different pressures. These results are plotted in Figures 14, 15 and 16. Mass-transfer performance of the T-By trays compares favorably to that exhibited by the sieve trays. The sieve trays exhibited a limited capacity and turndown, presumably due to the absence of inlet weirs and higher open areas.

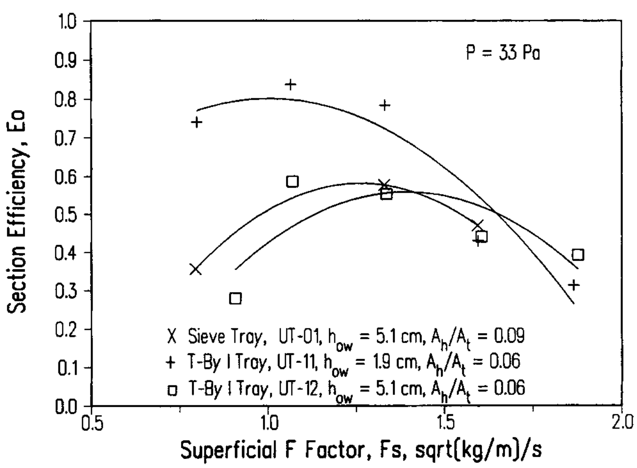

Figure 14. Section efficiency for two T-By and one sieve tray at an average pressure of 33 Pa.

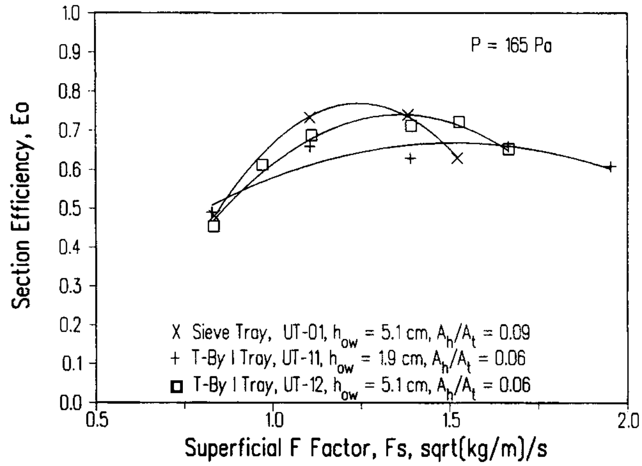

Figure 15. Section efficiency for two T-By and one sieve tray at an average pressure of 165 Pa.

T-By trays with shorter overflow weirs (h_{ow} = 1.9 cm, UT-11) exhibited excellent efficiency under vacuum conditions (Figure 14). During these tests, the trays operated in the spray regime so that the overflow weir height was not of great importance to efficiency. In the atmospheric and higher pressure columns (Figures 15 and 16), efficiency improved with the T-By tray using 5.1-cm overflow weirs.

The diameter of the test column in the University of Texas work (0.46 m) was not sufficiently large to demonstrate enhancement in mass-transfer efficiency as predicted by Brown (1936) and Lewis (1936). After all, this diameter column only allowed for three T-By cells and, even if complete plug flow could be achieved, the expected enhancement is small.

In these cases, the data for both the sieve and T-By trays approximated point efficiency, rather than efficiency as might result from larger diameter columns (for example, >2 m). These tests demonstrate, however, that T-By weirs and curtain-pattern vapor holes do not hurt point efficiencies. They also suggest that efficiency may be enhanced slightly, even in small-diameter columns.

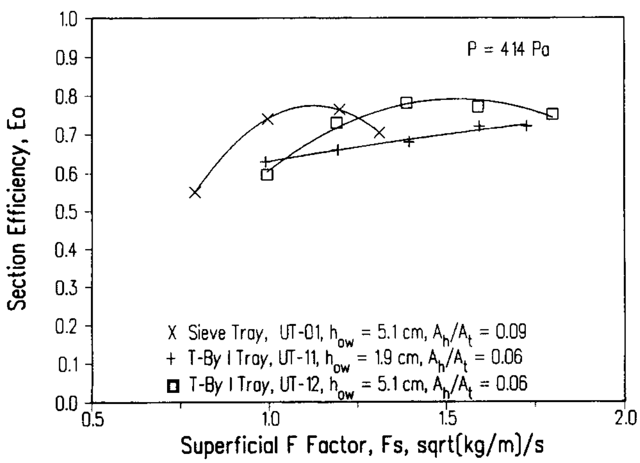

Figure 16. Section efficiency for two T-By and one sieve tray at an average pressure of 414 Pa.

Tray capacity and turndown

The University of Texas results indicate that pressure drops are lower for T-By trays with the same open areas as sieve trays. The T-By turndown and capacity characteristics appear to be superior to those of comparable sieve trays.

The Glitsch results indicate that the T-By trays have higher pressure drops and lower capacities than sieve trays with the same open areas. The T-By trays are more stable, however, as indicated by the results in Figures 12 and 13.

The UNI-FRAC results suggest that capacity and turndown are strongly affected by T-By cell dimensions. In the University of Texas study, $w_t = 6.99$ cm; in the Glitch test, $w_t = 17.78$ cm. The differences in these tests are attributed to w_t and the effect it has on cell vorticity.

Discussion

Lewis (1936) described how liquid plug flow can enhance the efficiency performance of a cross-flow tray. Brown (1936) pointed out that a series of positive contact zones on a tray will increase the plate efficiency significantly. Since then, there have been numerous attempts to design trays exploiting these potential benefits, but a practical design also must be simple, inexpensive, and not result in large increases in pressure drop per tray. While the goals outlined by Lewis and Brown seem straightforward, their practical implementation has been elusive.

The T-By tray attempts to exploit these potential benefits by providing an effectively rectangular flow path for the liquid that promotes plug flow. The idea of using T-By weirs perpendicular to the liquid flow path can improve liquid plug flow and provide a series of small mixing cells within the tray. The latter feature has the potential of providing a series of positive contact zones as suggested by Brown, but its effectiveness must also exploit liquid circulation patterns that are induced by a curtain-pattern of vapor holes and the T-By cell dimensions. Inappropriate hole patterns or T-By cell dimensions, however, can lead to excessive pressure drops per tray and reductions in tray capacities.

All of our results indicate that T-By weirs greatly stabilize liquid froth. Theoretical considerations suggest that T-By weirs also promote plug flow, but this point has not been clearly proven. Similarly, theoretical considerations suggest that T-By weirs, as part of a mixing cell, can promote froth vorticity and reduce pressure drop across a tray. Our results on this point are reasonably consistent with this hypothesis.

T-By weirs also complicate tower startup, and this point must be clearly understood by users. In particular, it is essential to flood all cells on each tray over the T-By weir height h_t to avoid vapor bypass before any benefits can be realized. Initial tray flooding is also essential for sieve tray operation, but it is more difficult to achieve with T-By trays, because the T-By weirs prevent liquid movement across a tray until all cells have been filled.

Conclusions

These results suggest that T-By trays can improve performance. The studies at all three locations indicate that intermediate weirs increase froth stability and height over a wider range of operating conditions. T-By trays with lower overflow weirs than conventional sieve trays still have more stable froth and greater heights over a wider range of operating conditions. Higher froth heights also result in some reduced capacity.

The increased froth heights also increase the net-wet pressure drop. The Glitsch results indicate that the net-wet pressure drop can be significantly higher than conventional sieve trays. The University of Texas and Salt Lake City studies suggest that the net-wet pressure drop may be significantly less than that for comparable sieve trays. We attribute the difference in these results to the differences in w_t and the ability to conserve angular momentum within the cells of the trays used by UNI-FRAC and by the University of Texas, but not in the trays used by Glitsch. Additional studies are needed to confirm these results and to determine the extent to which froth vorticity can be conserved to reduce vapor work and net-wet pressure drop, consistent with the model described using Eqs. 9–11.

The University of Texas studies indicate that the T-By tray does not reduce tray efficiency and suggest that it may increase efficiency, especially for vacuum operation. The column diameters in these tests, however, were too small to prove conclusively the effect of T-By tray operation on increasing overall tray efficiency, especially with respect to Lewis' model.

It is clear from these results that tray hydraulics can be used to affect performance in significant ways that have not been considered by other investigators. Tray hydraulics can be used to improve vapor-liquid contact efficiency, and intermediate weirs are especially effective in promoting stable froth and more easily controllable froth heights.

Higher net-wet pressure drops may result from a stabler froth, but this potentially adverse effect can be partially offset by conserving the froth rotational momentum within cells and by reducing vapor work in passing through the tray. It can also be offset by reducing the liquid holdup on a tray. The latter possibility is greater for T-By trays than sieve trays because of their increased stability over a greater range of operating conditions.

Notation

A_b = active bubbling area, m^2
A_d = area of one downcomer, m^2
A_f = A_h/A_b, the hole to active area ratio
A_h = area of holes or perforations, m^2
A_n = net area for vapor flow, m^2
A_s = area of one stagnant zone, m^2
A_t = tray total cross section, m^2
d_h = vapor hole diameter, cm
D = column diameter, m
E_o = section mass-transfer efficiency
$\hat{E}_v$ = frictional losses per unit mass of fluid, J/kg
F_s = $u_s\rho_g^{0.5}$, (kg/m)$^{-0.5}$/s
h_{cl} = clear liquid height, cm
h_{dt} = dry tray pressure drop, cm of liquid
h_{in} = inlet weir height, cm
h_L = total froth height, cm
h_{nw} = net-wet pressure drop, cm of liquid
h_{ow} = overflow weir height, cm
h_r = residual pressure drop, cm of liquid
h_s = T-By side riser height, cm
h_t = T-By weir height, cm
h_{wt} = wet or total pressure drop, cm of liquid
I = rotational inertia, kg·cm^2
$\dot{m}_g$ = mass rate of vapor sparged into a cell over length W, kg/s
$\dot{m}_L$ = mass rate of liquid overflow across a cell, kg/s
n = total number of vapor holes per tray
n_c = total number of vapor holes per cell

P = pressure, Pa
Q_g = gas or vapor flow rate, m^3/s
Q_L = liquid flow rate, m^3/s
r = radius of rotation for a differential element of fluid, cm
u_s = Q_g/A_b, superficial vapor velocity, m/s
v_x = velocity in x-direction, rectangular coordinates
v_y = velocity in y-direction, rectangular coordinates
V_c = horizontal liquid velocity in T-By cell, m/s
V_g = vapor or gas velocity entering a T-By cell, m/s
V_L = liquid velocity overflowing a T-By weir, m/s
V_r = rotation velocity of fluid, m/s
w_t = T-By cell width, cm
W = weir length, m
$\hat{W}$ = work on surroundings per unit mass of fluid, J/kg

Greek letters

μ = froth viscosity
ρ_c = average froth density, kg/m^3
ρ_g = the vapor density, kg/m^3
ρ_L = the liquid density, kg/m^3
σ = surface tension, dynes/cm
θ_1 = contact angle between V_L and the vortex stream function
θ_2 = contact angle between V_g and the vortex stream function
ω = froth vorticity in a T-By cell, radians

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