Protruded Sieve-Tray Performance

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The application of the sieve tray to cross-flow mass transfer equipment has expanded in recent years. The use of this type of tray results from lower construction costs and a number of design and operation advantages such as low entrainment levels, negligible hydraulic gradients, and low liquid inventory in the column.

A restrictive factor however exists. Although the use of sieve trays results in pressure drops lower than the bubble cap in the most operating regions, the orifice type of behavior to vapor flow results in a rapid change of pressure drop with vapor flow ($\Delta P \sim U^2$). Thus if a wide flow range of operational stability is desired, the bubble cap tray may at times provide lower pressure drops at the maximum operating rate. This phenomenon can be a limiting factor in the selection of tower internals.

The sieve tray is essentially a plate containing multiple sharp-edged orifices. The pressure drop through this configuration can be correlated with the ordinary orifice equation

$$\Delta P = cu^2 \qquad (1)$$

as indicated by Baines and Peterson (*1*), Liebson et al. (*3*), and Hughmark and O'Connell (*5*).

Inasmuch as the orifice loss is composed of entrance contraction, exit expansion, and eddy interaction losses, minimizing any of these losses should provide a significant decrease in the dry pressure drop of a sieve tray.

Venard (*6*) has indicated that replacement of a sharp-edged entrance by a nozzle type of entrance will decrease the overall orifice pressure drop by approximately one-third. The angle of entrance of the nozzle is critical, and with improper design not only can no advantage be gained, but an increase in pressure drop has been observed.

It was also hypothesized that a decrease in flat surface at the bottom of the sieve tray would promote the drainage rate of captured entrainment, thus decreasing the magnitude of reentrainment.

Evaluation was made of the effect of the geometry of the nozzle entrance on the pressure drop as a function of air flow through a single perforation and through multiple perforations. In the case of multiple perforations tests were conducted for both unirrigated and irrigated conditions. In addition evaluation was made of entrainment levels and tray efficiency for both conventional sieve trays and protruded sieve trays.

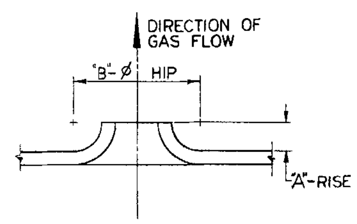
APPARATUS AND PROCEDURE

Single perforations

The diameter of the perforation used in this study was 3/16 in., and the plate thickness was 0.134 in., providing a t/D ratio of 0.72, well within the range of commercial operations. The various geometries utilized are indicated in Figure 1. Sufficient calming height below the orifice section was utilized in order to provide uniform flow of air in the duct prior to entrance into the orifice. Air flow was measured with a rotameter, and static pressure taps were provided on the circumference of the calming section for determination of the pressure drop through the orifices via manometer measurement.

Multiple perforations

This study was conducted with a tower 18 × 13 in. on cross section providing for 1 sq. ft. of active area on the tray.



PERF. DIA.-3/16"

	"A"	"B"
I	1/8"	0.5"
II	1/4"	0.5"
III	1/8"	0.4"
IV	1/4"	0.4"

Fig. 1. Configuration of protruded perforations, single hole test.

The tray spacing was 14 in. The downcomers consisted of three 3 in. diameter pipes with the lower portions submerged 1 in. in a 2 in. deep seal pan. A chord type exit weir 1 in. high was used on each tray. The rectangular tray was used in order to achieve the cross-flow behavior achieved in commercial columns. The bottom tray was of bubble cap design and used primarily for vapor distribution. Pressure drop and entrainment tests were run with the square-edged orifice perforated tray and the protruded sieve tray used in alternate positions, Tray 1 and Tray 2, in order to negate the effect of contraction eddies at the top of the tower that might affect the pressure drop effect in the Tray 1 position.

Both the square-edged perforated tray and the protruded tray had 7/32 in. diameter perforations and were 11% open.

Differential pressures were measured via manometer between the zone above Tray 1 and the zone between Trays 1 and 2 and between the zone tray 1-Tray 2 and the zone tray 2-Tray 3. Air flow was measured with the use of an orifice and liquid via a differential flow rotameter.

Entrainment measurements were made in the zones above an irrigated tray and above an unirrigated tray for entrainment passing through a tray via the method used by Cheng and Teller (*2*).

Tray efficiency and pressure drop data were also obtained for conventional sieve and protruded trays with the toluene-ethylene dichloride system at atmospheric pressure. In all cases the perforations were 3/16 in. diameter on 9/16 in. triangular spacing. The perforated tray dimensions were 3 in. wide by 12 in. long. Weir height was 1 in., and the downcomer area was 6 sq. in. Tray spacing was 18 in., and three trays were used in each test.

The trays utilized in the test evaluation were a protruded tray with 7/16 in. hip and 1/32 in. rise and a conventional perforated tray.

Bottoms concentration in all cases was maintained at approximately 50% ethylene dichloride.

Total reflux conditions were employed throughout providing a range of energy flow ($F = U_s \sqrt{\rho_v}$) ranging from 0.2 to 3.2.

RESULTS AND DISCUSSION

The comparison of pressure drop obtained with the single square-edged perforation and that obtained by Mayfield et al. (*4*) in a multiple perforation

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tray was made. Above a velocity of 1 std. cu. ft./min./perforation, excellent agreement with the data of Mayfield (4) was obtained. Below this velocity significantly higher pressure drops were observed with the single perforation and the slope of the log-log plot decreased to 1.67 at a capacity of 0.3 std. cu. ft./min./perforation. The deviation may have resulted from the fact that Mayfield used a significantly thicker plate (0.25 in.) resulting in a primarily long tube rather than sharp-edged orifice behavior (Figure 2).

The pressure drops for the various geometries used in the protruded perforation were compared with those of the sharp-edged orifice. In all cases a very definite decrease in pressure drop was obtained over the entire range of operation. The decrease in pressure drop for the various geometries is indicated in Figure 3. It is significant that the largest decrease occurs at low flows. This phenomenon is apparently related to the lower pressure drop obtained by Mayfield at low flows than that observed in this work or that of Arnold. The thicker plate used by Mayfield resulted in a partial tube behavior which resulted in significantly lower pressure drops in the region before the development of a high degree of turbulence. Inasmuch as the protruded length in the test perforations resulted in tube behavior, the results obtained are analogous to Mayfield's result.

It is noted in agreement with the estimated decrease in pressure drop

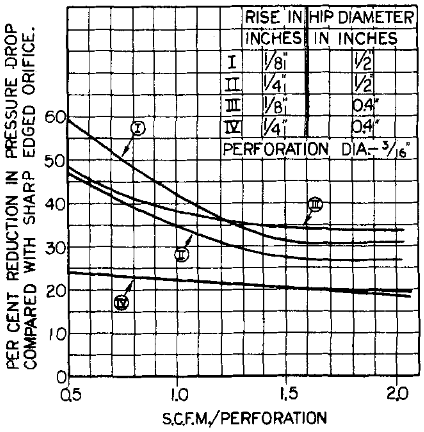

Fig. 3. Reduction in single perforation pressure drop as function of protrusion geometry.

predicted by Venard (6), that a decrease of approximately one-third of the permanent loss (under turbulent conditions) was achieved in one case by using the nozzle form of orifice (1/8-in. rise-0.4 in. hip diameter).

Of the four geometries evaluated the most effective perforation design from the aspect of minimum permanent energy loss had only a 1/8-in. rise of the protrusion above the tray. An increase in permanent head loss occurred with increase of length of the nozzle.

Multiple Perforation Test—Air Water System

The evaluation of the protruded tray in pilot scale equipment was made via a comparison with a sharp-edged orifice standard sieve tray with 7/32 in. D perforation, 11% open. The protruded perforations had a 0.4-in. hip diameter and a 0.1-in. rise above the tray.

In all cases duplicate tests were run with the protruded and standard sieve trays in the alternate positions, Tray 1 and Tray 2. Under dry conditions, with air flows ranging from $F = 1.1$ to $F = 2.3$ (based on perforated area), the pressure drop under dry conditions for the protruded sieve was approximately 50% that of the standard sieve tray (Figure 4). Under irrigated conditions a more consistent pattern of increase due to liquid head was exhibited (Figure 5). The decrease in dry pressure drop exceeded that anticipated from the results obtained with single perforations. It is attributed to the minimizing of the interaction of eddies normally created at the entrance to sharp-edged orifices, as well as the decrease in entrance loss.

This action may be hypothesized in the following manner. Whereas the dissipation of energy due to eddy formation occurs with no interaction at a single orifice, the condition of proximity of orifices in a sieve tray can result in fluid pattern effects at orifice entrances. Hughmark and O'Connell (5) have indicated in their empirical equation that the distance between perforations does affect the pressure drop in this manner via the percent open term.

Where the contraction of the fluid stream is more gradual, as in the case of protruded perforations, there is less eddy formation at the entrance to the orifices and interaction of the fluid streams with accompanying energy losses would thus be minimized, resulting in a greater decrease in pressure

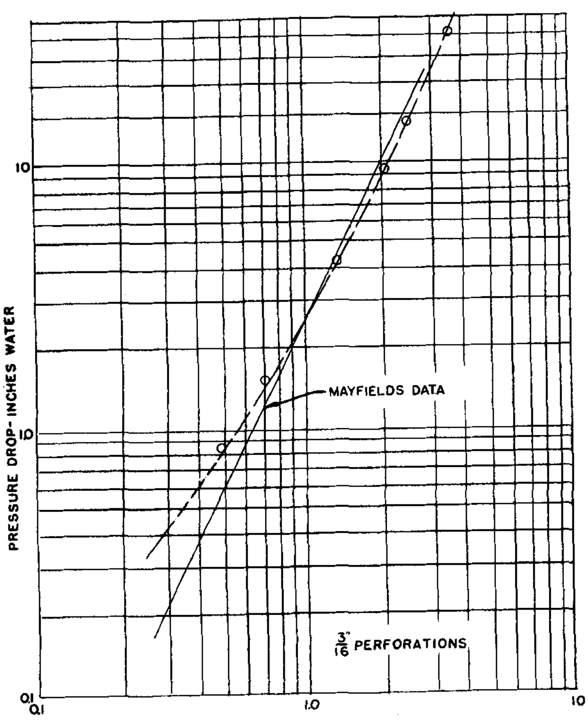

Fig. 2. Pressure drop, sharp-edged orifice.

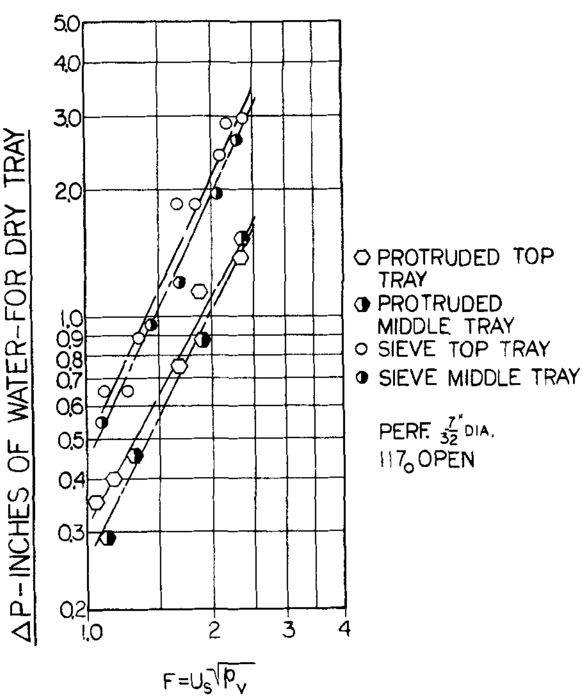

Fig. 4. Pressure drop of sieve and protruded trays (unirrigated).

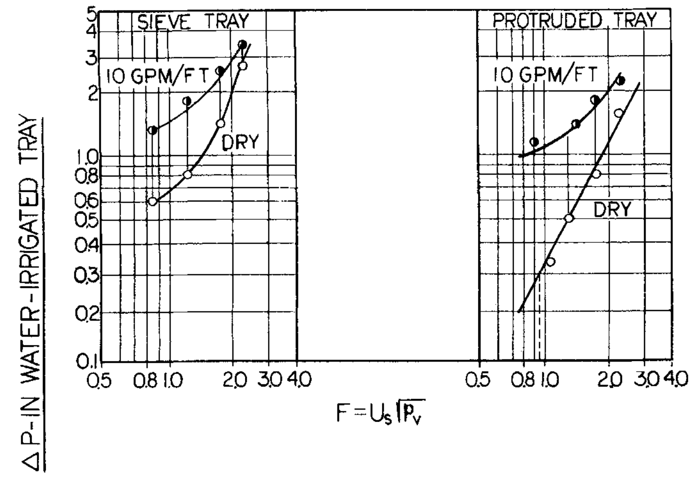

Fig. 5. Pressure drop for irrigated trays, air-water system liquid rate 10 gal./min./ft. weir weir height 1 in.

drop than anticipated with single orifice modification.

Entrainment tests were run via the position capture method (2) rather than gross dilution of tray liquid. The magnitude of entrainment between trays was essentially the same for both the conventional sieve tray and the protruded tray (Figure 6).

However a significant difference in the magnitude of captured entrainment, the quantity passing through a tray, was observed (Figure 7). Approximately 15 to 25% of the liquid entrained at the tray spacing level passes through the conventional sieve-tray perforations, whereas only 5 to 10% passed through the protruded tray. It is believed that this difference is due to the diminution of the re-entrainment phenomenon.

The tray itself, only 11% open, acts as an entrainment capture device. Thus liquid accumulates on the underside of the tray. In the case of a conventional sieve tray the liquid accumulates on the underside of the flat area between perforations (Figure 8). Sufficient liquid must accumulate until the weight of the liquid in the droplet formed is sufficient to overcome the surface tension forces. During this time the liquid is subjected to turbulent vapor flow created by the sudden contraction of the vapor at the orifice entrance. Thus some of it is pushed toward the orifice where it is entrained by the high velocity vapor stream.

In the case of the protruded perforated tray the flat area between perforations is significantly smaller than in the case of the conventional sieve tray. Thus the quantity of liquid necessary to overcome surface tension forces is less and the residence time of the liquid on the underside of the tray is less. In addition the sloping sides of the orifice nozzle and the decrease in vapor flow turbulence results in the decrease of probability of re-entainment.

Weep rates were visually observed for both the conventional and protruded sieve trays for the air-water system. Incipient weeping in the conventional sieve occurred at an energy flow factor $F = 0.87$ and for the protruded sieve at $F = 0.91$ with respective pressure drops of 0.34-in. water for the conventional sieve tray and 0.21-in. water for the protruded sieve tray.

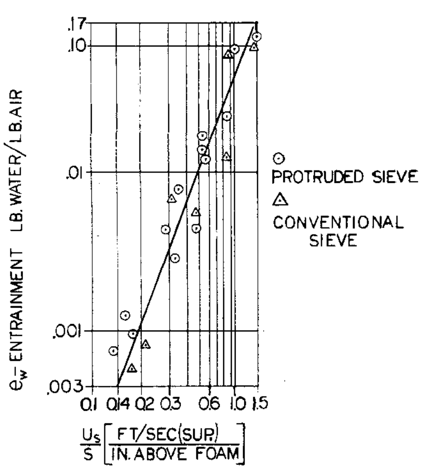

Fig. 6. Free entrainment between trays.

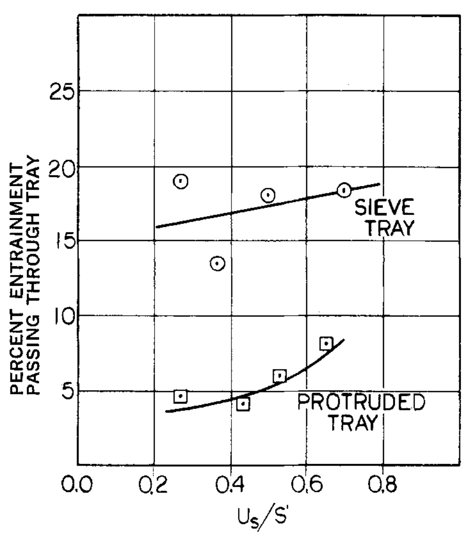

Fig. 7. Percent of free entrainment passing through the tray (both trays 7/32 in. diameter perforated, 11% open).

PRESSURE DROP AND EFFICIENCY DATA IN DISTILLATION SYSTEM

The pressure drops for the two types of trays are indicated as a function of energy flow (F) in Figure 9. When one confirms the prior work with the water-air system, a significant decrease in pressure drop is obtained with the use of protruded perforations.

At rates below $F = 0.5$ significant weeping was observed for all trays, and low efficiencies were observed (Figure 10.) The protruded Tray A and conventional sieve Tray B reached equal efficiencies in the region of $F = 1.5$. Beyond this throughput the efficiency of the conventional perforated tray began to decrease, whereas the protruded sieve tray maintained a relatively constant efficiency up to an F value of 3.2 (the limit of reboiler capacity). Inasmuch as the diffusivities and flows were equal in these operations, and the dispersion geometry was the same in both cases, the difference in efficiency can be related to the difference in degree of entrainment at this tray spacing.

Utilizing the Colburn approximate equation for the effect of entrainment on efficiency, modified for the total reflux system, one obtains

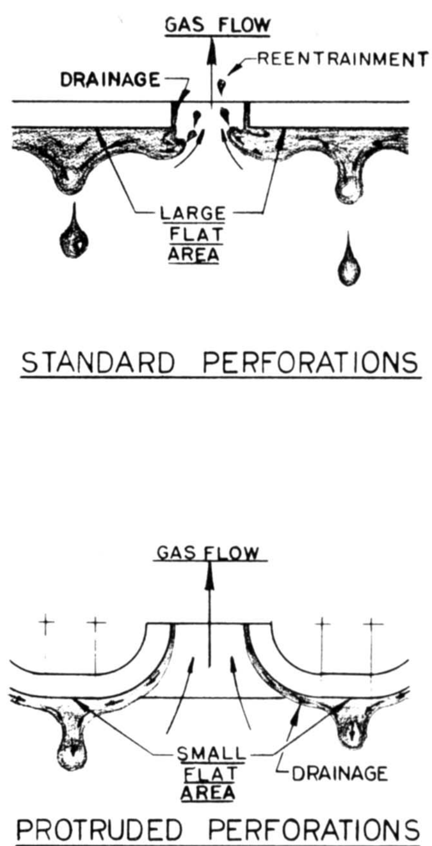

Fig. 8. Mechanism of re-entrainment.

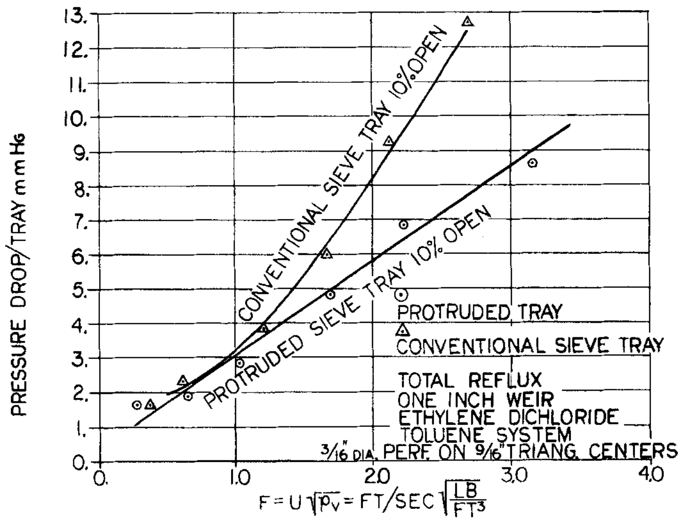

Fig. 9. Pressure drop comparison.

$$\left(Ea = \frac{Ev}{1 + eEv} \right)$$

The entrainment level was calculated by the relationship

$$\left(e = \frac{Ev - Ea}{EvEa} \right)$$

Inasmuch as the entrainment level is negligible in the region of $F = 1$, and since no significant increase is apparent in the case of the protruded tray up to a value of $F = 3$, Ev was assumed as 0.91.

Back calculating the entrainment level for the conventional sieve tray corresponded with the data obtained by Hunt et al., correcting for surface tension of the system. The comparison was as follows:

Entrainment for Conventional Sieve Tray

F	E_a	U_s/S equiv.	e(calculated)	e(Hunt et al.)
1.5	0.89	0.31	0.025	—
2.0	0.88	0.41	0.037	0.036
2.5	0.85	0.51	0.077	0.075
3.0	0.79	0.61	0.16	0.13
3.2	0.75	0.65	0.22	0.19

In the case of the protruded tray the effect of entrainment on tray efficiency was first noted at flows in the magnitude of $F = 3$. The calculated entrainment at $F = 3$ was 0.04, approximately one-fourth that of the conventional sieve tray, in essentially the same magnitude of the results obtained experimentally with the air-water system.

SUMMARY

Evaluation of the hydrodynamic performance of nozzle entrance (protruded) sieve trays and conventional sieve trays indicated that significant decrease in both pressure drop and entrainment can be achieved by use of nozzle entrances. The best results obtained in this study for single perforations was with a protrusion angle of 20 deg., where a reduction of 33 to 35% in dry pressure drop was observed in the flow range of 1 to 2 std. cu. ft./min./perforation.

Approximately 50% decrease in pressure drop and more than 50% decrease in captured entrainment was observed for the protruded sieve tray when compared with the conventional sieve-tray performance in a tray tower, for the water-air system.

A wider range of stable operation and lower pressure drop were obtained with the protruded tray compared with the conventional sieve tray in the distillation system, ethylene dichloride—toluene. Maintenance of efficiency through an F value of 3.2 was observed for the protruded tray, whereas diminution of tray efficiency for the conventional sieve tray occurred beyond an F value of 1.8, reflecting a significantly lower entrainment quantity in the protruded-tray operation.

NOTATION

- e = entrainment level lb. vapor/lb. liquid
- Ea = apparent tray efficiency including effect of entrainment
- Ev = Murphree vapor efficiency
- F = column energy capacity factor, $U_s\sqrt{\rho v}$
- S = calculated height above foam tray spacing minus 2.5 (clear liquid height)
- u = vapor velocity through perforations
- U_s = superficial vapor velocity in column
- DP = pressure drop across tray
- ρ_v = vapor density

LITERATURE CITED

1. Baines, W. D., and E. G. Peterson, *Trans. Am. Soc. Mech. Engrs.*, **73**, 467 (1951).
2. Cheng, S. I., and A. J. Teller, *A.I.Ch.E. Journal*, **7**, (1961).
3. Liebson, I., R. E. Kelley, and L. A. Bullington, *Petrol. Refiner*, **36**, No. 2, p. 127 (1957).
4. Mayfield, F. D., W. L. Church, A. C. Green, D. C. Lee, and R. W. Rosmussen, *Ind. Eng. Chem.*, **44**, 2238 (1952).
5. Hughmark, G. A., and H. E. O'Connell, *Chem. Eng. Progr.*, **53**, 127-M (1957).
6. Venard, S. K., "Elementary Fluid Mechanics," 3 ed., pp. 217-18, Wiley, New York (1954).
7. Hunt, C. d'A., D. N. Hanson, and C. R. Wilke, *A.I.Ch.E. Journal*, **1**, 441 (1955).

Manuscript received April 19, 1962; revision received September 25, 1962; paper accepted October 30, 1962. Paper presented at A.I.Ch.E. New York meeting.

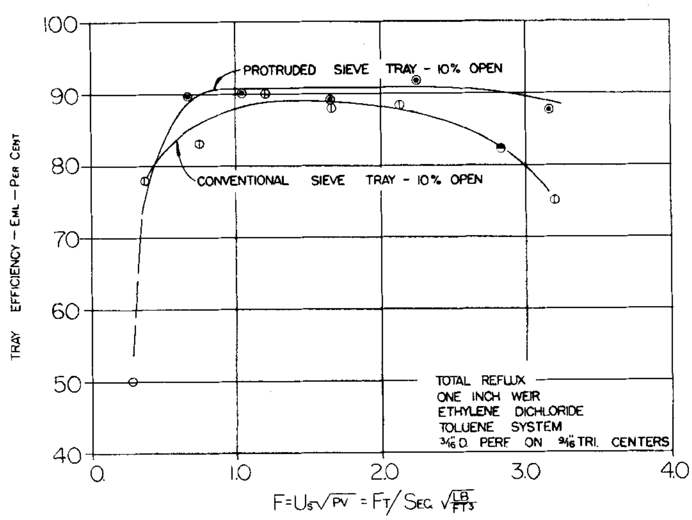

Fig. 10. Tray efficiency comparison.