Designing Crossflow Trays for High Weir Loadings

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Prepared for presentation at
AIChE Spring Annual Meeting, New Orleans, Louisiana
March 10-14, 2002

Abstract

Traditional design guidelines for valve and sieve trays limit the weir loadings to 100 – 120 gpm/ft. These limitations often require tray designers to increase the number of flow passes, increase tray spacings or utilize less-efficient counterflow tray designs when designing trays for high liquid rates.

The rapid development of high-performance tray technologies has given designers the tools and experience to design crossflow trays with substantially higher liquid rates. Tray designs with liquid rates exceeding 200 gpm/ft of weir have been field- and laboratory-demonstrated with good performance. These designs require a detailed understanding of tray and downcomer hydraulics and an adaptation of older tray correlations and design criteria to provide dependable designs at such high loadings.

This paper discusses the challenges of highly liquid loaded tray designs and illustrates the ability of crossflow trays to operate effectively at high outlet weir loadings. This is accomplished through utilization of theoretical concepts that are supported with research data and successful commercial applications.

Introduction

Neophyte distillation tray engineers can readily appreciate that overly-high downcomer liquid velocities and bubbling area vapor velocities are deleterious to the hydraulic and separation performance of distillation trays. High downcomer velocities recirculate vapor; high bubbling area velocities recirculate liquid. The dangers of high weir loadings, however, are less obvious. The units of weir loadings, for example "gpm per foot," leave engineers "wondering" rather than "fearing." What would happen if a tray were operated at 150 gpm per foot? Is that a high or low value? Does weir loading really represent a horizontal velocity?

Fifty years from now, it might be possible to accurately simulate the froths, crests, downcomer bi-phases, inlet regions and disengagement spaces of distillation trays functioning in air-water service. At that time, tray design will be a "science." In the meantime, however, it is an engineering discipline requiring daily judgments. Junior tray engineers still need to ask senior tray engineers, "How high can we go on weir loads?" Those senior engineers continue to think, "How many times do I need to answer this question - - - and I wish I had a more definitive answer." For both, valuable information is provided herein.

Existing Weir Loading Criteria

An excellent discussion of downcomers and downcomer hydraulics can be found in Henry Kister's "Chemical Engineering" paper[1]. Summarized therein are the need for vapor-liquid disengagement at the tops of downcomers and the choking that can occur above central, off-center and off-side downcomers that do not employ anti-jump baffles.

Many companies use a weir loading criterion that converts to approximately 100 USgpm/ft. Recent distillation practice has shown that this criterion is conservative. The tray design manual of Nutter Engineering[2] provides the following:

Tray Spacing, Inches	Increase Number of Passes If Weir Load Exceeds, Usgpm/ft
12	36
15	60
18	96
21	120
24	156

This conveniently-simplistic table does not account for the impact of different system physical properties – and has also proven to be conservative.

What's Wrong With High Weir Loadings?

High volumetric liquid-to-vapor ratio systems include the following:

- Seawater deaerators
- Refinery column pumparounds

- Steam or reboiled strippers
- Acid gas absorbers and regenerators
- High pressure distillation columns

Tray hydraulicists regard the columns earliest in the above list as the easiest to design, especially those where vapor rates are low or those where efficiency is not critical. Conversely, the columns latest in the list, where fluid density differences are low or where foaming occurs, are regarded as considerably more difficult.

Glitsch Equation 13 is possibly the best known correlation[3] for determining tray capacities and is shown below:

$$\frac{\%\ Flood}{100} = \frac{Vload \ + \ (GPM * FPL/13000)}{AA * CAF}$$

Knowing that weir length is approximately equal to AA divided by FPL, the following restatement can be effected:

$$\frac{\%\ Flood}{100} \approx \frac{(13000 * Vload) \ + \ (wl * AA)}{13000 * AA * CAF}$$

where wl is the weir loading. This latter correlation shows how weir loading impacts flood point. The numerator of each of the above correlations can be regarded as having a vapor and a liquid component. The liquid component is rarely insignificant, and in fact can comprise as much as 50% of the total.

As pointed out by Hanson et al[4], weir loadings impact tray capacities in at least two ways. High weir loadings create deep froths. If the spacing between trays is short, as in Figure 1, high tray-to-tray liquid entrainment can result and jet flooding can occur. In other cases where weir loadings are high, crests over outlet weirs become large in proportion to downcomer widths, and choke flooding occurs. This is shown in Figure 2.

How Can Trays Be Designed To Accommodate High Weir Loadings?

Obviously, the extent to which a high weir loading will impact a tray's capacity will depend upon the outlet weir height, the downcomer width and the tray spacing. For new designs, increasing the number of flow passes is the time-tested solution to excessive weir loadings, but there are limitations. At small diameters, a large number of flow passes proves to be mechanically impractical, and extremely short flow path lengths are alleged to cause efficiency problems. At large column diameters, flow passes exceeding four have been used only rarely. Fluid channeling can occur, especially with an odd number of passes (especially 3).

Sweptback outlet weirs, modified arc downcomers and anti-jump baffles have also been used routinely to alleviate weir-loading-initiated jet and choke floods. Additionally, push valves and mini valves such as those that are employed on SUPERFRAC, NYE and Bi-FRAC trays can be employed to reduce froth heights where weir loadings are high.

Morehead et al[5] reported that upstream relief downcomers have also been used effectively to avoid flooding on high-weir-load trays. Such downcomers create additional area for downward liquid flow. They also create a vapor-liquid disengagement zone, upstream of the main downcomer, to facilitate the feeding of the main downcomer with a less-aerated liquid. Such a configuration is shown in Figure 3.

What Weir Loadings Have Been Handled Successfully In The Lab?

One of Koch-Glitsch's laboratory apparatuses is a 7-foot diameter column that operates using air and water as the test fluids. It is located in Dallas, Texas. The physical properties of the air-water system make it easier to handle, with trays, than those that are encountered in industrial hydrocarbon columns.

Figure 4 shows capacity data from the Dallas column. The y-axis represents the vapor rate where 10% liquid entrainment was encountered. Some might call the y-axis "useful vapor capacity." Four different SUPERFRAC tray configurations are compared against conventional valve trays. Most noteworthy about the graph are the extremely high weir loadings that the trays were run at. One of the SUPERFRAC trays was run at 300gpm/ft. Even the conventional trays were run at almost 200 gpm/ft. In none of these cases was the highest weir loading tested regarded by the laboratory investigators as a maximum. Testing was halted at the weir loadings shown in the graph for a variety of different reasons. The SUPERFRAC trays were seemingly capable of running without flooding above 300; the conventional trays were seemingly very capable of running above 200. All of the data of Figure 4 were taken at 18-inch trays spacings.

Table 1 presents additional data from the Dallas 7-foot air-water column. For several different tray configurations, the maximum weir loadings that were tested are shown. Again, none of these weir loadings were regarded as true hydraulic limits. Again, tray spacings of only 18-inches were tested.

The Dallas air-water data suggest that all trays, and especially Koch-Glitsch high-capacity trays, are capable of functioning at extremely high weir loadings – as long as room exists for the froths, and the collapsing crests.

What Weir Loadings Have Been Handled Successfully Industrially?

Koch-Glitsch's global engineers were recently surveyed in an attempt to identify columns that were operating at extremely high weir loadings. Table 2 presents the results. It appears as though loadings like 200 gpm/ft can be accommodated, even in hydrocarbon systems, as long as tray spacings like 24-inches are available. In none of these cases was the weir loading regarded as the limit.

Why Can Trays Handle Such High Weir Loadings?

As stated previously, trays with large tray spacings and downcomer widths handle high weir loadings particularly well. For geometrical reasons, extremely high weir loadings are rarely ever encountered by distillation tray designers. Prohibitively high downcomer velocities are encountered first. Imagine a tray on which 24% of the column-cross-sectional area is downcomer area. Then imagine if the downcomer area were reduced by 8 factor. As shown in Figure 5, the downcomer velocity changes, obviously, by the same factor of 8.0. The weir loading, however, varies by a factor of only 2. Although it would be an exaggeration to state that all distillation trays function at the same weir loading, it is probably true that no industrial column is asked to function above 300 gpm/ft. A downcomer velocity limit will always be encountered first.

The modified Francis weir correlation[6] and droplet ballistics formulae from High School Physics also provide valuable clues regarding distillation trays' abilities to handle high weir loadings. For the case of a weir length greatly exceeding the crest height, the modified Francis weir correlation easily reduces to the following:

$$q = 0.415 * L * h_c^{1.5} * \sqrt{2g}$$

The ratio of q to L is the weir load, designated hereafter as "wl".

Figure 6 summarizes the results when the Francis correlation is manipulated and combined with a droplet ballistics analysis. First, crest height is seen to vary to the 2/3 power of weir loading. This has a dampening effect. If the exponent were 3/2 instead of 2/3, a small change in weir loading would have a large impact on crest height – and froth height and flood point. As seen in Figure 6, the impact of weir load on horizontal crest velocity is even smaller. "t_i" in Figure 6 is the impact time, i.e., the time it takes a liquid droplet to hit the inside of the column wall. As shown in the figure, impact time depends on weir load to only a 1/3 exponent. Again, this has a dampening effect on crest hydraulics – and an exponent greater than 1 would be deleterious. Finally, the vertical distance that a liquid droplet falls before impacting the column wall varies with weir loading to the 2/3 power.

All of the exponents above "wl" in of the equations of Figure 6 are less than 1. The hydraulic implication is that, regarding high weir loadings, distillation trays are surprisingly forgiving. Figure 7 presents two scale drawings. In Case 2, the liquid rate is 8 times that of Case 1. Notice how the crest height is only 4 times higher. The column wall impact points are also drawn to scale. For once, distillation tray engineers get a break. High weir loadings on distillation trays are accommodated surprisingly graciously.

(It should be noted that the modified Francis weir formula was derived based on unaerated liquid and very deep crests. Also, this droplet ballistics analysis does not account for the fact that vapor is rapidly escaping the biphase flowing over the outlet weir. This vapor surely drags liquid droplets and liquid sheets upwards. A simple droplet ballistics analysis will, in fact, never successfully predict a choke flood, unless the impact of the escaping vapor is included in the analysis.)

Summary

In the lab and in the field, crossflow distillation trays have proven capable of accommodating extremely high outlet weir loadings. At such loadings, crest and froth heights are high, but tray flooding will not occur as long as tray spacings are sufficient. Additionally, the high crest heights will not cause choke floods as long as downcomer widths are sufficient. A Francis weir and droplet ballistics analysis corroborates the fact that very high weir loadings are not necessarily disastrous. Existing weir loading criteria are probably generally overly simplistic. The ability to calculate crest heights at high weir loadings is probably of more importance to successful tray design.

Acknowledgements

Chuck Griesel supervised the collection of the air-water laboratory data from the Dallas 7-foot column. David Lin, Dave Simpson, Jurgen Muller, James Bailey, Ian Buttridge, Neil Sandford, Mike Sicinolfi and Daryl Hanson provided field data. Mike Binkley suggested the rearrangement of Glitsch Equation 13. Ralph Weiland provided technical support on several issues. The authors appreciated the efforts and results of all of these busy and excellent distillation technologists.

References

1. Kister, H.Z., "Downcomer Design for Distillation Tray Columns", Chem. Eng., Dec. 29, 1980, pp. 55-60.

2. FLOAT VALVE DESIGN MANUAL, Nutter Engineering, P.O. Box 7008, 639 W. 41st Street, Tulsa, OK 74105-0008, Aug. 1981, Rev. 1, pp. 10.

3. BALLAST TRAY Bulletin 4900, GLITSCH, INC., 4900 Singleton Blvd., Dallas, TX 75212, 1993, pp. 14-26.

4. Hanson, D.W., Becker, T. and Resetarits, M.R., "FCC Debutanizer Revamp for Flexibility and Additional Capacity", AIChE Spring National Meeting, Houston, TX, Apr. 22-26, 2001.

5. Fan, L., Morehead, P., Wu, K. and Lee, A., "New Downcomer Technology To Expand High Performance Tray Capacity", AIChE Spring National Meeting, Houston, TX, Mar. 12, 1997.

6. Perry's Chemical Engineers' Handbook, 7th Ed., Perry, Robert H., Green, Don W. and Maloney, James O., editors, McGraw-Hill, New York, NY, 1997, p. 10-19.

7. Fractionation Research, Inc Monthly Progress Report, January 1966, on deposit in the Special Collections section of the Oklahoma State University Library.

Figure 1
Jet Flood

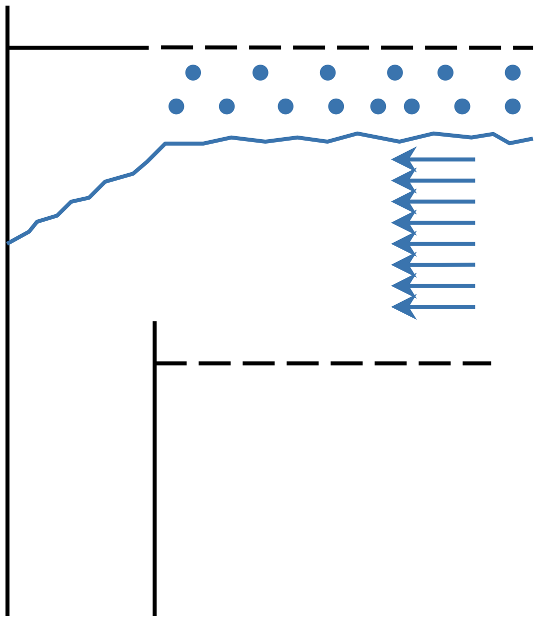


Figure 2
Choke Flood

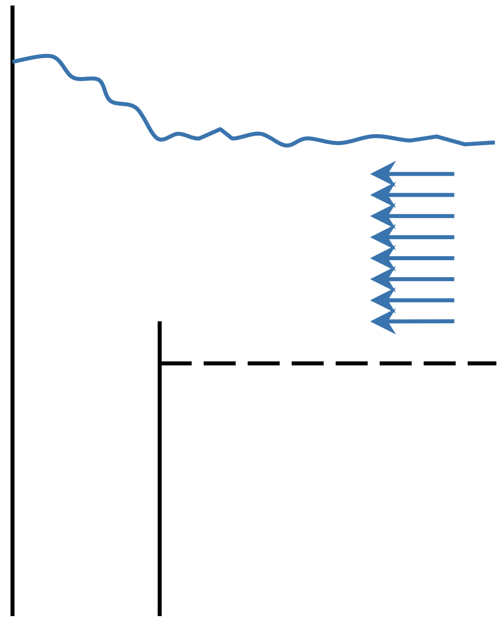


Figure 3
SUPERFRAC 4

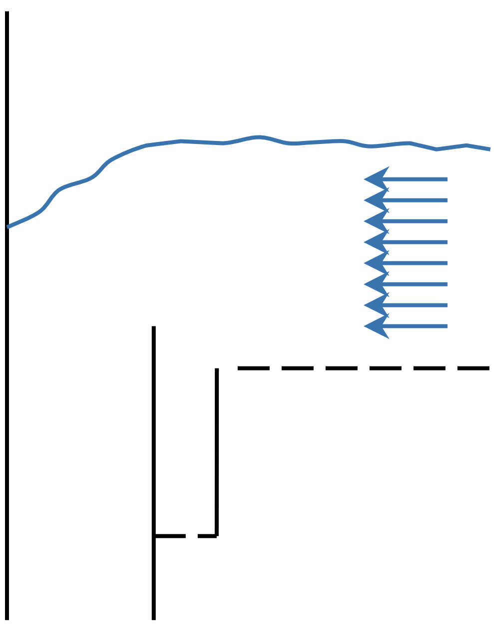


Figure 4
Capacity Chart for Crossflow Trays

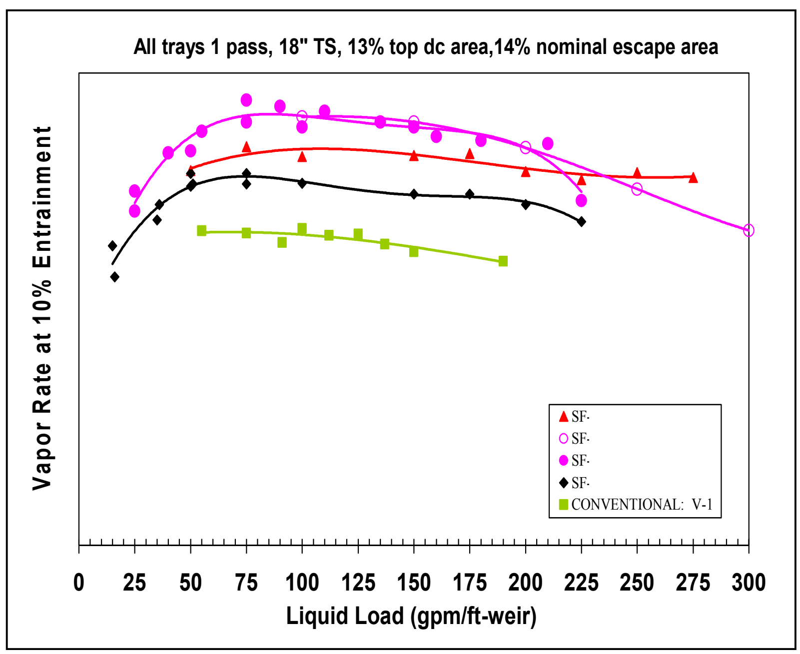


Table 1

LABORATORY OPERATING POINTS			
Air-water system Tower diameter = 7 feet Tray spacing = 18 inches for all Downcomer curtain clearance maximum = 3.5 inches			
Tray Type	**Deck Type**	**No. Passes**	**Weir Load USgpm/ft**
SUPERFRAC	MV-1, VG-0, V-1	2	204
Sieve	0.5-inch holes	1	193
Valve	V-1	1	190
Valve	VG-0	1	183
MAX-FRAC	Type T	1	160
NYE	V-1	1	250
NYE	VG-0	1	225
SUPERFRAC 3	VG-0	1	300
SUPERFRAC 3	MV-1	1	300
SUPERFRAC 4	VG-0	1	300
Note: In all cases, the trays were capable of handling even higher weir loadings.			

Table 2

COMMERCIAL OPERATING POINTS					
Application	**Tray Type**	**Tower Diameter**	**No. Passes**	**Tray Spacing, Inches**	**Weir Load, USgpm/ft**
Product Stripper	Conv. Valve	9 ft	2	27	230
Deethanizer	SUPERFRAC	5 ft	1	24	171
Crude Twr – PA	Bi-FRAC	25.5 ft	2	30	191
Crude Twr – PA	SUPERFRAC	14.3 ft	2	36	218
VGO Stripper	Sieve	9.8 ft	2	29.5	235
Stabilizer	SUPERFRAC	10 ft	2	24	211
Deethanizer	Sieve	7.5 ft	2	24	174
Debutanizer	SUPERFRAC	5.6 ft	2	24	157
Crude Twr – PA	NYE TRAYS	14 ft x 20 ft	2	30	240
FCC Main Frac – PA	Bi-FRAC	24 ft	2	36	240
FCC Debutanizer	SUPERFRAC	10.5 ft	2		190
C3 Splitter	NYE TRAYS	11.5 ft	2	18	145
Crude Twr - PA	Conv. Valve			30	214
Stripper	Conv. Valve	10 ft	2	24	225
FCC Debutanizer	SUPERFRAC	9.5 ft	2	24	218
Crude Twr – Stripper	Sieve	16 ft	2	24	166

Figure 5

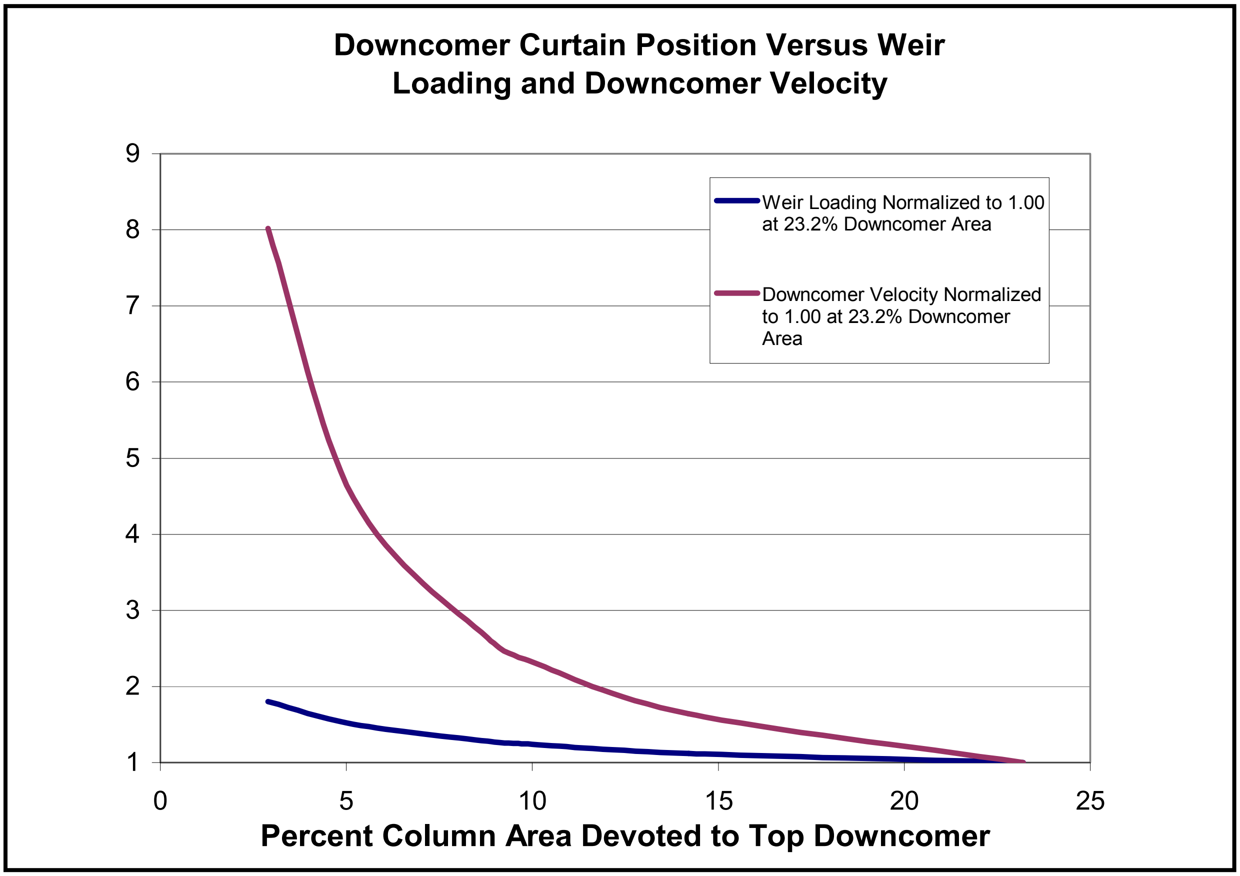
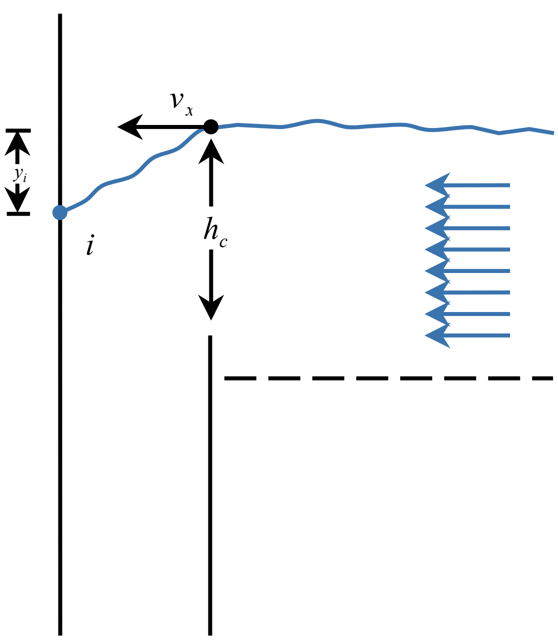


Figure 6
Modified Francis Weir Analysis



$$h_c = 0.449 \ wl^{0.667}$$

$$v_x = 2.23 \ wl^{0.333}$$

$$t_i = 0.448 \ H \ wl^{0.333}$$

$$y_i = 3.23 \ H^2 \ wl^{0.667}$$

Figure 7
Impact of 8-Factor Liquid Rate Increase