Design Considerations for High Liquid Rate Tray Applications

Mark Pilling
Sulzer Chemtech USA, Inc.

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Introduction

Except for a few odd services, high liquid rate applications are typically the domain of either trays or random packings. Aside from the distributors, random packing designs are rather straightforward with the designer choosing the proper size to accommodate the fluid flow rates and achieve the desired efficiency. Trays, on the other hand, have a large variety of adjustable parameters. This paper will focus on trays because of their complexity, especially when designed for high liquid rate applications.

Characteristics of High Pressure Distillation Systems

Generally, the most difficult type of high liquid rate application is high pressure distillation (as opposed to stripping/absorption or heat transfer). High pressure distillation services have four characteristics that can make tray design quite challenging.

They are:

- High Liquid Rates
- Low Density Difference between Vapor and Liquids
- Low Surface Tension
- Low Efficiency (above certain pressures)

High Liquid Rates

High pressure distillation services have naturally high liquid flux rates. This is actually due more to the vapor properties than the liquid properties. High pressures create high vapor densities and corresponding low vapor volumes. For example, a column processing hydrocarbons and operating at atmospheric pressure is likely to have a vapor density of around, 0.4 lb/ft3. A high pressure depropanizer can have a vapor density of 3 or 4 lb/ft3. This is an order of magnitude difference. Since the majority of a distillation column's cross sectional area is devoted to vapor handling, high pressure columns will always have smaller diameters than lower pressure columns processing a similar mass rate. Also, high pressure distillation usually involves lower molecular weight components that have a lower liquid density. This can increase in the volumetric liquid flow rate by 40%. The net result is that high pressure distillation applications use a smaller diameter column while handling a much larger proportion of liquids.

Vapor/Liquid Density Difference

High pressure distillation applications also have a significantly lower density difference between the vapor and the liquid phases. This adds a whole new degree of difficulty to tray designs. As the density difference decreases, it becomes exceedingly more difficult to separate the vapor and liquid phases because the vapor buoyancy in the liquid decreases. This creates a need for significantly larger downcomers. The extreme case is critical pressure, where no separation can occur due to the lack of a density difference.

Surface Tension

High pressure distillation applications typically have significantly lower surface tension which creates additional difficulties in the tray operation. High surface tension liquids, like water, form nice big droplets. Big droplets are much easier to coalesce and much less likely to be entrained to the tray above. Low surface tension liquids form significantly smaller size droplets that are much more susceptible to entrainment to the tray above.

Efficiency

Above a certain pressure level, higher pressure systems have lower efficiencies. With standard hydrocarbon separations, a debutanizer typically achieves the highest efficiency with commercial scale values of around 90%. Separations of lighter hydrocarbons (depropanizers, deethanizers, and demethanizers) yield lower and lower efficiencies as the pressures increase. This is generally due to increases in liquid viscosity and relative volatility, both of which directly lead to lower efficiency.

Basic Tray Design Considerations

When dealing with high liquid rate tray designs, the first question that must be addressed is how to effectively move this large amount of liquid through the tower. Gravity helps with the downward movement but the lateral movement of a high density fluid requires energy and control. The designer must carefully control the liquid momentum and use that momentum for the benefit of the operation.

Trays operating at very high liquid rates rarely fail from a deck or jet flood limitation. They nearly always fail from lack of liquid handling capability. Therefore, proper sizing of the downcomer is critical. There are several criteria used to size downcomers. Most of these are semi-empirical, based on a combination of theory and what has worked successfully in the past. These criteria are discussed in more detail below.

<u>Downcomer residence time:</u> This rather empirical limitation is not used as commonly today as other criteria. Given a known liquid volumetric flow, a residence time requirement sets a minimum acceptable downcomer volume. Since most trays are on 24” tray spacings, this then defines a minimum acceptable downcomer cross-sectional area. In simpler terms, the residence time requirement is simply a minimum acceptable downcomer velocity that varies as a function of tray spacing. On one hand, this makes sense since bubbles in the froth will reach some equilibrium penetration depth into the liquid pool in the downcomer. However, the backup level in the downcomer is essentially independent of tray spacing. If a tray configuration and associated hydraulics require a 14” backup in a downcomer, that backup will be 14” regardless of whether the tray spacing is 18” or 24”. So from this perspective, the residence time requirement doesn’t seem be as useful as some of the other criteria and correlations.

<u>Downcomer Velocity:</u> More modern downcomer sizing correlations are based mainly on downcomer velocity. Downcomer velocity is calculated as clear liquid flowing through the downcomer top cross-sectional area. The preferred correlation for many companies is from the Fractionation Research, Incorporated (FRI^{SM}) Topical Report 123[1]. This correlation is based on a variety of physical properties and process variables which have been fit to the vast amount of data collected at FRI. It uses an iterative solution based on drag calculations to predict the ability for a bubble to rise in the downcomer. Table 1 shows VGPlus^{TM} tray operating data from FRI and the corresponding ratings. As can be seen, the correlations from TR-123 matched the performance very well under heavily loaded conditions.

<u>Weir loading:</u> This is another often used parameter for tray ratings. It is calculated as the clear liquid volume divided by the length of the tray outlet weir. This value has a direct influence on the froth height on the tray as higher weir loadings increase the fluid crest over the weir. The crest height over the weir is calculated from the Francis weir formula or some slight derivation thereof. Basically, crest over weir varies with the weir loading to the 2/3 power. As the weir loading increases, the crest over weir and the liquid/froth level on the tray increase with it. This increase has several effects:

First, increased crest over weir raises the liquid level on the tray deck which increases the pressure drop across the deck. This creates higher downcomer backup. Increased weir loading also decreases the distance between the top of the froth on a tray deck and the bottom of the tray above which can lead to higher entrainment levels. This can cause interference between the froth flowing across the tray and the structural members supporting the tray above. When combined with a long flow path and a high open area tray, this may lead to vapor cross flow channeling[2]. Finally, the higher crest over the weir can also cause choking of the downcomer or jumping of intermediate downcomers with multi-pass trays.

Downcomer Head Loss (exit or spout velocity): The velocity out of the downcomer is also a closely controlled variable. The is important for two reasons. First, high velocities create unwanted momentum on the tray deck. Too much momentum can adversely affect both the vapor and liquid distribution on the tray. Second, high velocities lead to high orifice head losses at the downcomer outlet. As mentioned earlier, the frictional loss of liquid flowing though the downcomer contributes to downcomer backup. The downcomer outlet is the greatest restriction in the downcomer so the velocity through this portion must be maintained within proper limits. A general guideline is that the outlet velocity should not exceed 1.5 ft/sec or create a pressure drop in excess of 1 inch of clear liquid. This value is controlled by varying the downcomer clearance height. In lower liquid flow applications, most designers prefer to keep a positive seal on the downcomer by keeping the outlet weir height at least 0.5 inches greater than the downcomer clearance. In high liquid rate applications, the downcomer clearance required may be in excess of 3 inches in order to reach an acceptable outlet velocity. In this case, a negative seal may be used, where a weir height of less than the downcomer clearance, in an effort to limit the tray pressure drop.

Downcomer Flood Mechanisms

The effects of high liquid rates on downcomer operations are rather straightforward. As the loading in the downcomer increases, the downcomer can flood from three main methods: choking, backup, and excessive vapor carryunder. Although choking and flood are the two classic flood methods, excessive carryunder is also a failure of the downcomer because the downcomer is no longer accomplishing its fundamental task of separating vapor and liquid prior to delivering the liquid to the tray below.

Downcomer choke occurs when the top area of the downcomer is inadequate to handle the high froth flow, preventing effective vapor disengagement of the vapor. This causes the liquid to back up onto the tray deck until the column floods. This is generally evaluated semi-empirically as a function of the clear liquid velocity in the downcomer. In high pressure systems, this clear liquid assumption becomes less and less realistic since the fluid entering the downcomer will actually be a mixed phase froth and the volumetric flow rate can be several times higher than a calculated clear liquid velocity. As a result, many high pressure applications use system factors to derate the tray capacity. A typical system factor will derate the downcomer by 10% - 25% while a more severe system may require the expected tray performance to be derated by 50%. Severe foaming systems may require derating the trays even further.

Downcomer backup flooding occurs when the hydraulic head requirements to flow liquid through the downcomer exceed the height of the downcomer itself. The liquid level in a downcomer behaves in a similar manner to a manometer as shown in Figure 1. The head level equilibrates to whatever is necessary to create a steady state flow of the liquid to the tray below. Downcomer backup is a function of the tray pressure drop, the head at the inlet side of the tray, and the frictional losses in the downcomer itself.

Downcomer carryunder occurs when the froth in the downcomer does not completely clarify and vapor bubbles are allowed to travel fully through the downcomer and exit the bottoms. This is usually only a concern in high pressure applications, especially with shorter tray spacings. Vapor carryunder recycles vapor through the column and artificially loads the tray and also decreases efficiency due to backmixing. Sulzer uses a correlation derived from FRI Topical Report 123 to evaluate the possibility of vapor carryunder.

Tray Design Strategies

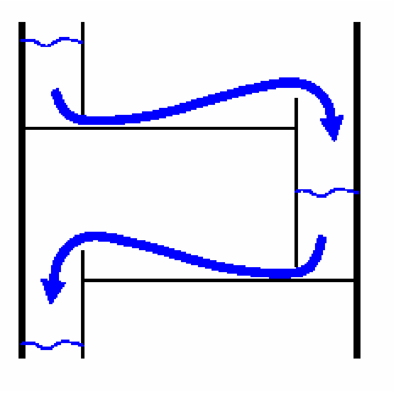
Once the allowable downcomer velocity is determined, then the downcomer must be sized accordingly. With a smaller diameter tower, the tray will be a one pass design so the side downcomer top width needs to be sized to achieve the desired downcomer velocity. Since the downcomer area will likely be a significant portion of the column area, sloping the downcomer (making the bottom width smaller than the top width) will save some bubbling area and provide a more efficient design. Sloping downcomers makes sense because the froth density in the downcomer increases as the froth degasses as it travels down the downcomer. This decreases the volumetric flow so a smaller cross sectional area at the bottom of the downcomer will help to create a relatively constant velocity through the downcomer.

After the downcomer area is established, the other rating factors must be evaluated. Weir loading needs to be kept below 13 gpm/inch of weir. A notable exception to this rule is for atmospheric pressure column pumparound sections. Since these applications are found in low pressure applications where vapor and liquid separate rather easily, they are not limited as strictly as high pressure distillation applications. Also, pumparound sections are used primarily for heat transfer which is a fast process and can more easily handle any maldistribution that may be found with high liquid rate applications. Pumparound sections have been known to operate well with weir loadings in the region of 18 gpm/inch as long as the tray is otherwise properly designed.

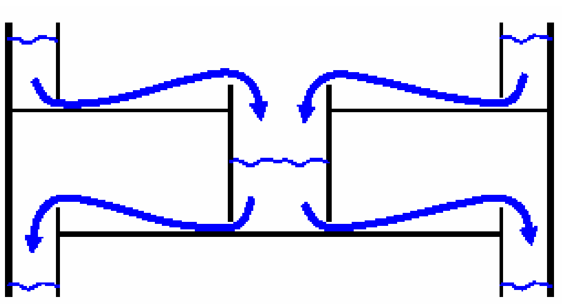
When the weir loading is too high, the following methods may be used to create an acceptable design.

Multipass Trays

The most common method of dealing with high liquid rates (aside from making the downcomers larger) is to increase the number of passes on the tray. By splitting the liquid into multiple flow paths, the weir loading can be decreased significantly. For example, a 12 ft diameter tower with a single moderately sized downcomer and a weir loading of 16 gpm/inch of weir can be redesigned with a two pass layout and achieve a weir loading of 11 gpm/inch or a 4 pass layout with a weir loading of about 8 gpm/inch. One mechanical restriction that can be encountered with multiple passes is available flow path length. Typically, a minimum flow path length of 16" is maintained in order to allow for a tray manway to be installed and accessible for maintenance. A two pass tray usually will have to be at least 6 ft in diameter and a 4 pass tray will require a minimum diameter of 12 ft. Three pass trays with chordal downcomers are asymmetric and typically not recommended. Sketches of one and two pass designs are shown below.



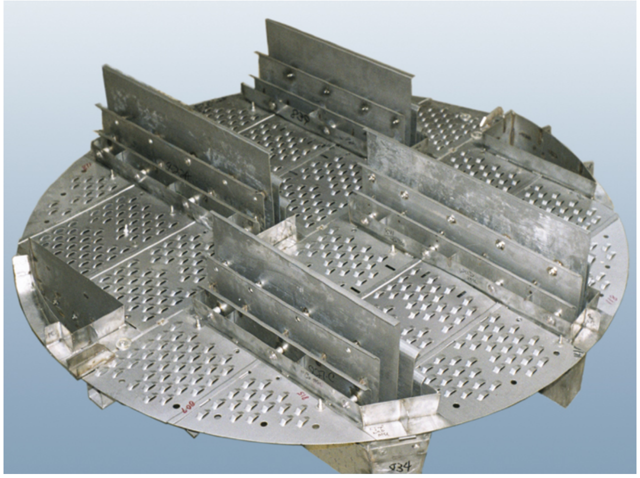
One Pass



Two Pass

Multiple Downcomer Trays

For very high liquid loads, special multiple downcomer trays can be used, such as the Shell Global Solutions HiFi™ trays (shown below). These designs typically use several downcomers to create a substantial weir length per tray and thereby provide a minimum practical weir loading for an application. This type of tray is most commonly used in superfractionators (C_2 and C_3 splitters) where a very large number of stages are required in a high pressure, high liquid rate application.



Shell Global Solutions HiFi Tray

Conclusion

Tray designs in high pressure applications can be quite challenging. Because the liquid side is so dominant in these applications, you must make every effort to get the downcomer design and sizing correct. To create a well conceived design, you must first understand the fluid properties and their implications with respect to the tray hydraulic operation. You must then design the downcomer(s) following the proper methods and criteria while making sure that the vapor side handling is adequate as well. The real challenge is to simultaneously meet all those criteria while maintaining an acceptable column diameter. This is especially true with revamps where the column diameter is fixed. The process of meeting those criteria will lead you towards the proper tray layout and pass configuration and provide you with a sound and workable design.

Bibliography

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2. Kister, H.Z. and Poul E. Madsen, "Vapor Cross-flow Channeling on Sieve Trays: Fact or Myth?", Chemical Engineering Progress, Nov. 1992, pp. 86-96

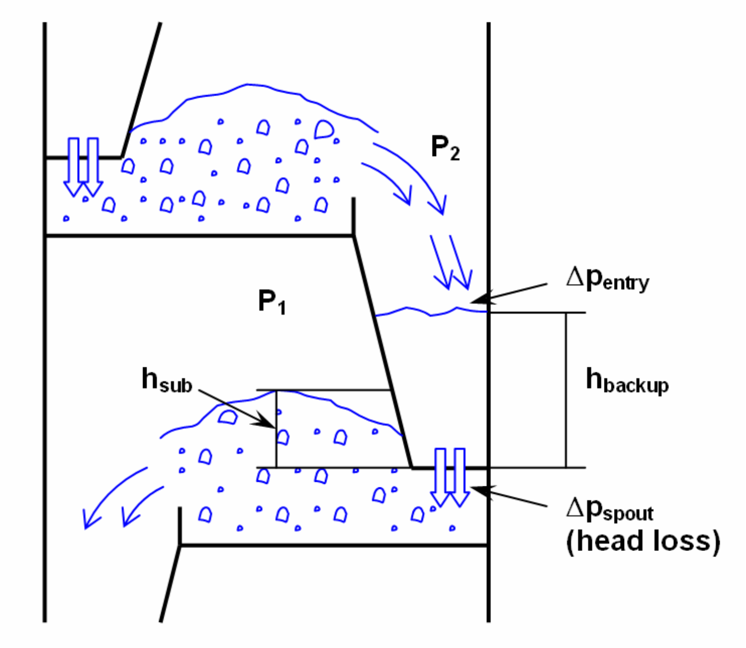

Figure 1: Downcomer Pressure Balance

FRI VGPlus Results

System	iC4/nC4	iC4/nC4	iC4/nC4	iC4/nC4
Pressure	165	165	165	165
Run Type	TR	TR	TR	TR
Useful Capacity, %	100	101	104	106
FRI Downcomer Velocity, %	**95**	**94**	**98**	**100**
Downcomer Velocity, ft/s	0.367	0.374	0.387	0.396
Weir Load, gpm/inch	8.0	8.1	8.4	8.6
Efficiency	102	102	97	86

Table 1: Downcomer Velocity Ratings