Choosing Trays and Packings for Distillation

Tower-related problems can be difficult, time-consuming, and expensive to diagnose and fix. Here's how to avoid difficulties and improve operating efficiency.

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Distillation towers are essential to the chemical process industries (CPI), so it is imperative that they are properly designed and operated. Tower internals are arguably the most important piece of process equipment, since they cannot easily be accessed after startup. If the tower internals malfunction, the distillation tower will follow suit and the entire chemical process will suffer.

This article explains how process simulations of the distillation tower provide the necessary data for engineers to select proper tower internals. These internals can be trays or packings, each of which has a set of characteristics that makes one more appropriate for a particular separation application than the other.

Understand the process

Selection of distillation tower internals requires an understanding of the purpose of the separation, the required range of vapor and liquid flows, and the physical properties of the vapor and liquid throughout the tower. Much of this information can be obtained from a process simulation of the distillation tower. These data, together with the vapor-liquid equilibrium and physical property models, determine the optimum number of stages and reflux ratio, as well as product purity and the column's economics.

System characteristics that affect the design and construction of the tower internals, including constraints such as maximum temperatures, fouling tendencies, and ongoing chemical reactions, must be carefully evaluated. In addition, the corrosivity of the process fluids and their sensitivity to contamination dictate the selection of materials of construction for the internals.

Once the designer understands these considerations as well as the hydraulic requirements of the separation, the tower internals can be selected and designed.

Trays vs. packings

Tower internals can be trays, random packing, or structured packing. Generally speaking, trays are used in applications with liquid rates of 30 m³/m²-h and above, and/or those where solids are present or fouling is a concern. Structured packings are typically used in lower-liquid-rate applications (*i.e.,* less than 50 m³/m²-h), especially where minimizing column pressure drop is important. For similar applications, packings can be expected to have a pressure drop that is a fraction of the pressure drop across trays. Random packings are often used in higher-liquid-rate

applications where lower pressure drop is desired.

These liquid-rate guidelines are not absolute. When trays operate with weir loadings less than 20 m³/m-h, structured packings should be evaluated as an alternative. When structured packings operate at liquid rates above 50 m³/m²-h, then trays or random packings may be better solutions. However, there is often significant overlap of the liquid flowrate ranges of various types of packings. It is always recommended to evaluate all practical solutions and then select the best design.

The liquid loading in a distillation column is a function of the column pressure, because the vapor and liquid molar flowrates are nearly equal. At low pressures, the difference in vapor and liquid densities is much larger than at higher pressures. For example, a column processing hydrocarbons at atmospheric pressure may have a liquid-to-vapor-density ratio of well over 100, whereas a high-pressure application will have a liquid-to-vapor-density ratio of less than 10. From a volumetric standpoint, this means that higher-pressure distillation applications will have a higher proportion of liquid than will lower-pressure or vacuum applications.

In many cases, the choice of trays or packing can be very complex, so the engineer must consider the impact of many factors in making the best choice for an application. These factors are discussed below.

Tray operation fundamentals

Distillation trays generally provide holdup for a portion of liquid through which vapor flows to accomplish the vapor-liquid mass transfer required for separation. With a conventional crossflow tray, the liquid travels horizontally across the tray and into a vertical downcomer while the vapor passes up through holes or passages in the tray and across the flow of liquid. Countercurrent trays (such as dual-flow trays) have no downcomer, and the upward flowing vapor and downward flowing liquid compete for passage through the holes in the tray deck. Crossflow trays are much more common in commercial practice than countercurrent trays because of their (typically) higher separation efficiency and wider operating range. However, some modern high-capacity trays employ countercurrent-flow designs, and are generating renewed interest in this arrangement.

Trays operate predominantly in either of two flow regimes — spray or froth. In the spray regime (Figure 1), which is found mostly at lower pressures, the vapor is the continuous phase and the liquid is dispersed as droplets. In the froth regime (Figure 2), the liquid is the continuous phase and the vapor bubbles through the liquid. This regime is more common and occurs at moderate to higher pressures.

Tray characteristics

Conventional crossflow trays (Figure 3) consist of a deck with an inlet region for liquid feed and a downcomer at the outlet. The deck is perforated for vapor flow, with the openings occupying about 5–15% of the deck area. The tray spacing between decks is most commonly 610 mm,
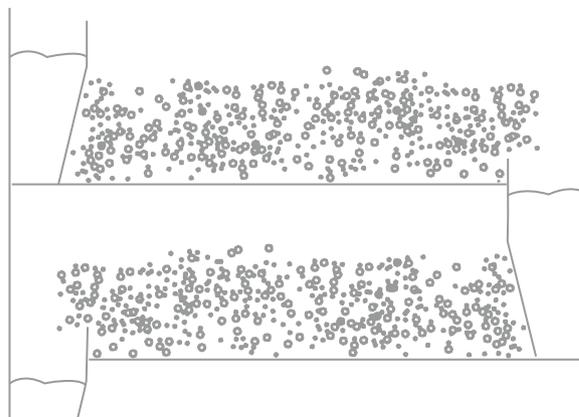
▲ **Figure 1.** The spray operating regime occurs mostly at lower pressures and has liquid droplets dispersed in vapor.
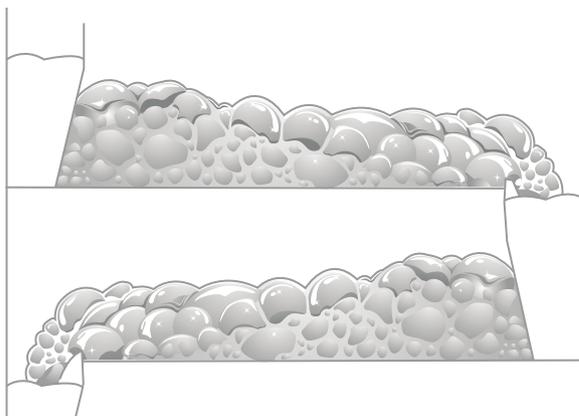
▲ **Figure 2.** The froth operating regime occurs at moderate to higher pressures and has vapor bubbles dispersed in liquid.
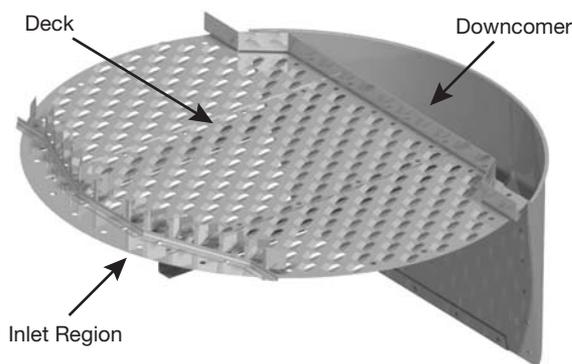
▲ **Figure 3.** The ideal tray design balances the areas required for the vapor and liquid flows.

and can vary anywhere from 300 to 900 mm. The down-comer size is about 5–30% of the tower cross-sectional area, depending on the liquid load. As with any tower internals, the ideal design balances the areas required for the vapor and liquid flows.

• *decks.* The purpose of the deck area is to create a mixing region for the vapor and liquid. Each deck has an inlet area where liquid is received from the downcomer above, and from there the liquid is redirected out onto the active area. Most decks have either sieve perforations or valves through which the vapor flows. A vertical weir at the outlet side maintains a liquid level on the tray deck sufficient to ensure good mixing with the vapor. The outlet weir height is typically about 50 mm. Frothy liquid from the active area overflows the weir and falls into the downcomer.

• *downcomers.* The downcomer's primary purpose is to provide a conduit for the frothy liquid to flow to the tray deck below. Its secondary purpose is to provide a calm

▲ **Figure 4.** Random packings are loaded into a column by dumping sacks or boxes of the packing into a tower section.

region where vapor disengages from the frothy fluid so the liquid exiting the bottom of the downcomer to the tray below is clear. Any significant amount of vapor traveling out the bottom of the downcomer is to be avoided, as it will reduce tray capacity and efficiency due to backmixing.

Tray operating limits

The operating limits of a tray are set to prevent weeping at low throughputs and flooding at high throughputs.

Weeping occurs when the vapor-side pressure drop across the tray deck is too low to support the liquid pool on the top side, so the liquid weeps through the holes. When the predicted dry-tray pressure drop falls below 12 mm H_2O, weeping may become a problem. A good rule of thumb is that 20% weeping leads to a 10% loss in efficiency.

Flooding occurs at the other end of the operating range. The tray deck generally floods by a mechanism called jet flooding, where excessive vapor velocities carry liquid droplets to the tray above. Entrainment is more detrimental to tray performance than weeping because it causes backmixing of the liquid. A good rule of thumb is that 10% entrainment causes a 10% loss in efficiency.

The downcomers may also flood due to backup or inlet velocity flooding. The froth level in the downcomer is set by the liquid head at the tray inlet (*i.e.,* the downcomer outlet), the pressure drop across the tray, and the frictional losses in the downcomer. As the tray pressure drop increases and the liquid rate increases, the froth level in the downcomer will increase. When the froth level, or downcomer backup, exceeds the downcomer height, the tray above will flood. Downcomer backup can be mitigated or avoided by increasing the spacing between trays, lowering the outlet weir height, decreasing the tray pressure drop, or increasing the downcomer clearance. Usually, increasing the downcomer size is not effective, because the frictional losses in the downcomer itself are negligible.

The other type of downcomer flooding is velocity flooding, which occurs when the velocity of the liquid entering the downcomer is too high for the frothy liquid to enter the downcomer (called choking), or when the velocity in the downcomer is too high for the bubbles to rise and disengage from the froth. Velocity flooding is usually a concern only in moderate- to high-pressure systems (*i.e.,* above 5 atm). This may be mitigated by increasing the downcomer size or sloping the downcomer.

There is a practical limit to the liquid loading that can be handled by a single tray pass. This is often calculated as weir loading in units of volumetric flowrate per unit of weir length. A good design guideline is that once the weir loading exceeds 90 m^3/m-h, increasing the number of passes will usually help. When designing a tray, start with a

single-pass design and progress to two- or four-pass trays if needed. Three-pass trays are seldom used because they are asymmetric and difficult to balance. Trays with liquid rates requiring more than four passes are somewhat rare and should be selected with care. These applications with very high liquid rates may be better served by random packings.

Random and structured packing fundamentals

Whereas trayed towers provide stepwise contact between the vapor and liquid phases, packed towers provide continuous contact without full disengagement of the vapor and liquid between the top and bottom of the packed bed.

Because of their inherently large open area, packed towers can operate with lower overall pressure drops than trayed towers and are often specified for vacuum service where reboiler pressures and temperatures are low. The definition of a "low" temperature is typically a function of the chemical system, which may be susceptible to product degradation. In cases where degradation is possible, lower temperatures are usually beneficial up to the point where extreme, very expensive measures are needed to reduce the temperature further.

Other advantages of packed towers are their generally shorter tower height, mechanical simplicity, ease of installation, and ability to be fabricated cost-effectively from corrosion-resistant materials, including plastics, ceramics, and other nonmetals. However, for efficient performance, they require good liquid distribution to the top of the bed, and achieving that reliably over years of service requires vigilant maintenance. In addition, packed towers typically do not handle solids well, which tend to get trapped in the bed and foul liquid distributors. And at high operating pressures, the low-pressure-drop advantages of packings over trays diminish.

There are two general types of tower packings — random and structured. Random, or dumped, packings (Figure 4) consist of many small pieces, in sizes ranging from 15 to 100 mm, that are loaded into a tower by emptying sacks or boxes of the packing into a tower section so that they randomly arrange themselves into a packed bed.

Structured packings (Figure 5) are typically constructed as blocks of alternating layers of thin corrugated sheet, gauze, or mesh, which can be fabricated from a wide range of metal alloys or nonmetals such as plastics, ceramic and graphite. This structure spreads the vapor and liquids evenly over the cross-section of the tower.

In general, structured packings create lower pressure drops and achieve better separation efficiencies with shorter bed heights than random packings, but they are also generally more expensive than random packings and are more time-consuming to install. Random packings are often preferred over trays or structured packings in corrosive services, especially where ceramics are required because of the presence of highly aggressive chemicals and extreme temperatures.

Both random and structured packings achieve separation by providing surface area for vapor-liquid mass transfer to occur. In random packings, smaller piece sizes result in more surface area per unit volume and higher separation efficiency, but with higher pressure drop and lower throughput. Conversely, larger random packings with less specific surface area will deliver lower separation efficiencies with lower pressure drop and higher throughput. Similarly, structured packings with more sheets and smaller corrugations will have higher specific surface areas and better separation efficiency but at a cost of higher pressure drop and lower capacity. Because higher surface areas require more material per unit volume, higher-surface-area packings are always more expensive than lower-surface-area packings on a cost per volume basis.

The separation efficiency of packings is often expressed in terms of the height of packing equivalent to a theoretical equilibrium plate (HETP). A theoretical plate, or stage, refers to the mixing or contacting of a vapor stream and liquid stream until the mixture reaches equilibrium with respect to heat, mass and composition. The resulting vapor and liquid streams from the equilibrium mixture are then either drawn off as products or flow to another equilibrium stage within the tower. The number of theoretical stages required for a particular separation depends on the operating conditions, process components, and product purity requirements,

◀ **Figure 5.** Many corrugated, perforated sheets (left) are fabricated into a structured packing element (right).

and is typically determined by a process simulation. This number and the HETP for a particular packing are used to determine the actual height of packing required to achieve the desired separation.

Liquid distribution

Good liquid distribution is critical for effective operation and efficient separation performance of both random and structured packings. Maldistribution has been reported as the most prevalent cause of problems in packed towers *(1)*.

In principle, the surface area of the packing needs to be fully covered and uniformly wetted by the liquid to maximize efficiency. However, there is a practical limit to the number of distribution points that can be provided while maintaining adequate fouling resistance and uniform liquid flow across the packing surface. For random packings 25 mm or larger, and most structured packings, 40–100 distribution points/m^2 are recommended for good performance, although up to 200 points/m^2 may provide better performance on small random packings and high-area structured packings with areas of 500 m^2/m^3 or more *(2)*.

The range of liquid flowrates that a distributor must handle, known as the turndown ratio, is an important factor that must be considered in design. If the liquid flow is lower than the lowest design value, liquid levels in the distributor will be too low, flows to individual drip points and different regions across the top of the packed bed will vary significantly, and separation efficiency will be reduced. If the liquid flow is higher than the packing's maximum design flowrate, liquid levels will be too high, overflows will occur, and separation efficiency will again suffer.

Liquid-distributor design for specific applications is a very complex topic, and experienced tower internals suppliers are best-suited to provide designs that will work properly to deliver good packing performance.

Random packing characteristics

Random packings come in a wide range of geometries: cylindrical rings, saddles, spheres, and various other shapes. Traditional shapes such as Raschig Rings (cylinders) and Intalox saddles have mostly been replaced by more modern designs such as Pall Rings, Nutter Rings, IMTP packings, and proprietary designs. Suppliers continue to develop novel shapes that deliver improved performance.

Random packings are usually characterized by their nominal size or diameter, although different packings of equivalent size may provide very different performance in terms of capacity and separation efficiency (modern packings typically offer significant performance advantages over the traditional designs). In small towers with any random packing design, a minimum tower-to-packing diameter ratio of 8:1 to 10:1 is recommended to minimize loss of

separation efficiency due to voids in the packed bed and wall effects *(2, 3)*.

Random packings are made from material of various thicknesses, so the maximum allowable bed depth for each packing needs to be considered carefully. This is especially true with plastic packings, which may experience some degree of crushing at the bottom of the bed that worsens at elevated temperatures due to plastic softening. Bed heights as tall as 12 m have been successfully operated, although these tall towers use larger packing. Even if a packing's mechanical strength can withstand a high bed depth, in order to maintain effective liquid distribution, a height of no more than 10–14 theoretical stages is recommended for a single bed without liquid redistribution *(3)*.

Structured packing characteristics

The base material for structured packing (Figure 6) is generally a thin (0.1–0.2 mm) metal sheet. Lower-surface-area packings have deeper crimping and therefore may require a thicker material for structural purposes. Since structured packing materials are very thin and have a large amount of surface area, there is essentially no corrosion allowance. Thus, material of construction is a very important consideration. Wire gauze packings fabricated from woven metal cloth are used for very-high-efficiency applications at low liquid loadings such as those at deep vacuum (although high-surface-area sheet-metal packings with high-quality liquid distributors are also successfully used in deep vacuum services).

The surface area of structured packings is almost always reported in metric units of m^2/m^3. Available surface areas commonly range from 40 m^2/m^3 to as high as 900 m^2/m^3. Packings in the range of 40–90 m^2/m^3 are often a specialized type of packing referred to as grid. Grid packings employ a unique heavy-duty design with a very large open area and high capacity. They are commonly used in services where fouling and hydraulic load stresses can be significant. Structured packings with very high surface area (*i.e.,* above 500 m^2/m^3) are typically used in air separations and production of fine chemicals.

The angle of the corrugations in structured packings is typically 45 deg. from horizontal, but can range from 30 deg. to 60 deg. for some applications. A common naming designation for structured packings uses the suffixes Y for 45 deg. and X for 60 deg.

As the corrugation angle increases, efficiency decreases, pressure drop decreases, and capacity increases. A 45-deg. angle usually provides the optimum combination of efficiency, capacity, and cost. A 60-deg. corrugation angle is more common in gauze packings.

The surface of most types of structured packing is textured and perforated. The texturing helps to promote

spreading of the liquid on the sheet itself, while the perforations promote flow and pressure equalization between individual packing sheets. In most services, packings with no surface texture or perforations will have significantly lower efficiencies.

Commercial-scale towers typically require a manway for insertion of internals. The individual packing layers need to be segmented into blocks small enough to be passed through the manway; once inside the tower, they are arranged so that all of the sheets are parallel. The pattern of the blocks (referred to as the segmentation pattern) is the same for each layer. Each successive layer is usually rotated 90 deg. from the previous layer to prevent the seams between blocks from aligning vertically. To further minimize the overlap of the seams between successive layers, the segmentation pattern typically has a staggered layout, which creates the most uniform bed and prevents vapor and liquid from flowing through the seams and bypassing packing blocks.

When to use structured packing

Structured packing's greatest process advantages are typically seen at lower pressures (*i.e.,* less than 2 atm) and lower liquid rates (*i.e.,* less than 50 m^3/m^2-h) due to its extremely effective vapor-handling ability. Vacuum to atmospheric pressure distillation is ideal for structured packing.

Some important criteria include:

• *system pressure.* In distillation, system pressure is a good indication of the relative liquid flowrate, which typically increases with pressure. As mentioned earlier, the biggest advantages of structured packings are usually realized at lower liquid rates. Low-pressure systems tend to have the lowest liquid rates and the highest vapor rates, which is ideal for structured packings.

• *vessel diameter.* The diameter of the vessel is more relevant for trays than packing. Trays with diameters less than 760 mm require special mechanical considerations. At smaller diameters, tray designs become less practical, and packings are almost always used.

Structured packings are limited by small tower diameters that change as a function of packing size. Larger-crimp packings have a larger minimum allowable column diameter. For example, a standard 250-m^2/m^3 packing has a minimum allowable column diameter of 100 mm. There is no upper limit on the tower diameter for structured packings.

• *presence of two liquid phases.* Care must be taken in applications where two liquid phases are present in the tower (regardless of the internals), as this presents unique challenges for both packed and trayed towers.

When using structured packings with two liquid-phase systems, several issues need to be addressed. Although liquid distributors can be designed to handle two liquid phases, their design requires much care. When two liquid phases are present, they tend to segregate on the packing surface, which reduces efficiency. The extent of these potential problems is very much system-dependent and should be evaluated on a case-by-case basis to determine the optimal type of internal.

• *number of stages required.* In applications where a large number of stages is required, structured packing is usually a better choice because it is highly efficient (especially relative to random packings). In some cases (*e.g,* superfractionators), trays are normally a better choice because of the high pressures and high liquid rates.

The mechanical layout of the bed and associated internals within the tower must also be considered. Since packed beds require distributors and collectors, a bed with very few stages may require more vertical space in the tower than a trayed section.

• *thermal degradation of the product.* In many processes where thermal degradation is a concern, the use of structured packing can provide two significant advantages. First, structured packing inherently has a very low liquid holdup, so liquid residence time in the bed is less, which minimizes degradation. Second, the lower pressure drop of structured packing allows distillation tower bottom sections to be operated at lower pressures and lower temperatures, which also minimizes degradation potential.

Performance characteristics of structured packings

The performance of structured packings is generally a function of the packing geometry and the vapor and liquid distribution systems. As stated earlier, larger-crimp,

▲ **Figure 6.** Structured packings are very thin, with a large amount of surface area and no corrosion allowance.

lower-surface-area packings will have higher capacity and lower efficiency.

The upper operating limit of structured packing can be expressed in terms of either useful capacity or hydraulic flood capacity. (The lower operating range, which is related more to the feed distribution, is addressed in the liquid distributor discussion.)

• *useful capacity (efficient capacity)*. As the loading on a packing increases, liquid begins to accumulate in the packed bed. This is referred to as liquid holdup. If the loading continues to increase, the packing will reach a point where the efficiency begins to decrease. Once the drop in efficiency is significant, the packing has reached 100% of its useful capacity.

• *hydraulic capacity*. If the loading increases beyond the packing's useful capacity, a state will eventually be reached where the amount of liquid holdup in the bed is sufficient to cause hydraulic flooding. Beyond 100% of hydraulic flood, tower operation will be unstable, as liquid and vapor are not able to flow freely through the bed. It is generally recommended to not exceed 80% of hydraulic capacity when rating conventional packing. When rating some high-capacity (S-shaped) packings, this limit can be increased to 90%, because these packings resist the buildup of liquids at the interface between the packing layers, which allows them to operate effectively at a higher loading than conventional designs.

• *pressure drop per theoretical stage*. Packing performance is sometimes evaluated in terms of pressure drop per theoretical stage. This is an important term because it measures the efficiency of the packing versus the hydraulic resistance. Since packing designs are usually a tradeoff between pressure drop and efficiency, the lowest pressure drop per theoretical stage indicates the most-effective packing type.

▼ **Figure 7.** In some high-performance structured packings, the corrugation intersections are curved rather than angular, which reduces resistance and liquid holdup.
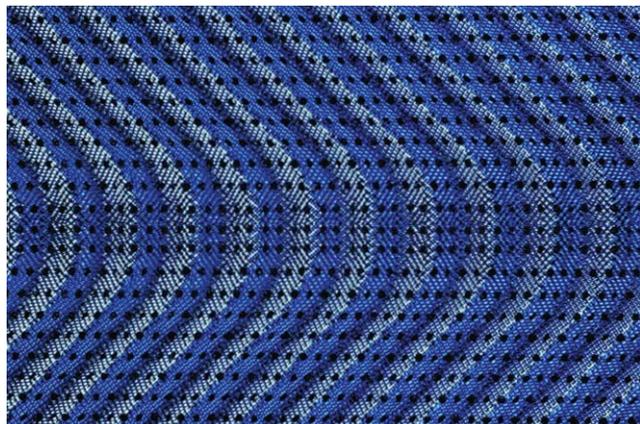
• *pressure drop*. A good guideline for the maximum acceptable pressure drop is 3 mbar/m of packing depth for conventional structured packing. This equates to approximately 100% of the useful capacity. Some high-capacity structured packings may be able to operate efficiently at higher pressure drops.

• *loading mechanism*. As vapor and liquid loads increase in a packed bed, liquid begins to accumulate (hold up) in the bed. One study found that with conventional structured packings, the liquid holdup begins at the horizontal interface between packing layers *(4)*. This occurs because of the irregularities in the packing structure at this interface, where the angle of the corrugations on two successive layers changes sharply. Within the past several years, mechanical designs of packing structures have been modified (such as shown in Figure 7) in an effort to minimize this effect.

Closing thoughts

Designing a distillation column requires understanding a variety of issues and making many choices related to the column internals. Understanding the process and the function of the internals is key to ensuring an effective design. Following the guidelines presented here will allow you to make more informed decisions. CEP

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