1.0 Abstract

Refinery vacuum towers present difficult challenges for mass transfer internals. They combine severe mechanical constraints, difficult process conditions, and large economic consequences of being wrong in any direction. This is a service that often lacks a clear-cut conservative or safe answer. This paper reviews the state of the art for internals in refinery vacuum columns. Equipment must meet both service and mechanical requirements.

Services commonly include heat transfer (pumparound), de-entrainment (feed entry and overhead) and stripping (trays). Less often, fractionation services may be included. In modern vacuum towers the dominant heat-transfer and fractionation choices include grid and structured packing. The major driving force is the low pressure drop of these devices. Additional benefits include good performance at low liquid loads.

The two major developments of recent years include high-capacity structured packing and improvements in two-phase feed devices.

Mechanical difficulties come from large equipment diameters and severe mechanical loads during upsets.
Auxiliary equipment to make the packing works include collectors, liquid distributors, and vapor distributors. These must also meet the service and mechanical requirements imposed by the process.

3.0 Dominant Equipment

3.1 Equipment Types

Structured packing and grid are the dominant fractionation equipment in vacuum towers. Pressure drop is the driving force behind this choice.

Structured packing works with elements of corrugated metal installed vertically. Liquid moves down the channels from one layer to the next. Vapor rises up the channels. Normal installation rotates the layers by 45° to 90° from each other.

Grid elements predate structured packing. Grids have very open structure and high mechanical strength. Original styles of grid acted more like splash baffles. Modern grid styles may continue to act that way, or may blur the distinction from structured packing.

Both structured packing and grid have major advantages for vacuum tower services;

- Low pressure drop, reducing operating pressure at tower bottom,
- High-turndown for both liquid and vapor rates,
- Operation at very low liquid rates, improved de-entrainment performance,
- High overall capacity, allowing for maximum capacity and minimum operating pressure,
- Low liquid residence time, reducing coking risks,
- Reasonable metal mass, allowing for use of expensive alloys at moderate cost.

Except for special applications random packing and trays are rarely used in modern vacuum towers. Special cases for tray applications include;

- Stripping sections, improved reliability in service,
- Lubricants towers with multiple side-draw products, simplified draw arrangements.

Random packing is rarely used in modern vacuum towers and has no special application niches.

3.2 Equipment Capacity Evaluation

Packing and grid can both be evaluated by two basic methods. These are flooding evaluation and C-Factor (or F-Factor) limits.

Conventional packing evaluation uses flooding calculations. The same approach can be used in vacuum tower services. As liquid rates in packing increase, some portion of the packing fills with liquid. Interaction between the rising vapor and falling liquid becomes more significant as this filling occurs. Packing correlations take this into account.

In refinery vacuum tower services, vapor volumes are very large for the feed rate. Tower cross section area requirements are dominated by the vapor handling requirements. This gives towers with large diameters. Process requirements set moderate-low to extremely low liquid rates for the tower cross section. Liquid volume in the packing is rarely significant. Under these conditions, a simpler C-Factor or F-Factor analysis is accurate, simple, straightforward and easily shows remaining system capacity.

The Souders-Brown C-factor is a simplified expression of Stoke's law for liquid droplet settling

\[ c_{SB} = \frac{v}{A_{CS}} \sqrt{\frac{\rho_l}{\rho_l - \rho_v}} \]
Where,

$c_{SB}$  the Souders-Brown C-factor, ft/sec (often shortened to C-factor and not using the subscript)

$v$  velocity of rising vapor, ft$^3$/sec

$A_{CS}$  cross sectional area open to flow, ft$^2$

$\rho_v$  vapor density, consistent units

$\rho_l$  liquid density, consistent units

Alternate methodology uses an even more simplified F-factor;

$$F = \frac{v}{A_{CS}} \sqrt{\rho_v}$$

Where,

$F$  F-factor, (m/s)(\rho_v)^{0.5} or (Pa)^{0.5}

$v$  velocity of rising vapor, m$^3$/sec

$A_{CS}$  cross sectional area open to flow, m$^2$

$\rho_v$  vapor density, kg/m$^3$

By convention, C-Factor calculations always use ft-sec units, F-Factor calculations most commonly use SI units, but are occasionally shown in ft-sec units. The conversion factor from SI to Imperial is to multiply by 0.8197 to get units of (ft/sec)(lb/ft$^3$)$^{0.5}$.

C-Factors include the effect of liquid density. The C-Factor equation is based on a force balance of the drag force of the rising vapor lifting droplets of liquid versus the gravity force on the droplets. Assumptions about droplet sizes, droplet shape, vapor viscosity and acceptable entrainment are built into a definition of accepted C-Factor limits for specific packings.

Different vendors publish C-Factor versus pressure drop and packing efficiency or F-Factor versus pressure drop and packing efficiency curves. The maximum C-Factor limit reliably demonstrated for an open structured packing or grid in a refinery vacuum tower is 0.45 ft/sec.

Higher surface area packings may have a lower C-Factor limit. Appropriate information should be provided by the packing vendor to evaluate a specific packing’s limit.

Vacuum towers often have different diameters in the various services. This reduces the overall investment by making the diameter smaller if the expected vapor load is smaller. For this reason, vacuum towers may be hydraulically limited in any section. However, for a constant diameter vacuum tower, the heaviest load will be at the top of the wash bed or bottom of the HVGO bed.

Both these locations see the same vapor rate. The vapor leaving the wash bed becomes the vapor entering the HVGO bed. They do differ in liquid rate;

- The HVGO liquid rate is much higher than the wash oil rate, potentially making the HVGO bed the higher load point.

- The wash bed has liquid entering it at the top. The impact of liquid on the metal surface of the packing or grid causes splashing, liquid film buildup on the top of the bed, and some liquid-entrainment up the column, potentially making the wash bed the higher loading point.

Except in extreme cases, the liquid dynamics at the top of the wash bed are more limiting than the extra liquid at the bottom of the HVGO bed.
4.0 Equipment Services

The basic equipment services in the refinery vacuum column include:
- Heat-transfer (always present);
- De-entrainment (nearly always present);
- Mass-transfer (occasionally present);
- Stripping (often present);
- Auxiliary equipment (always present);
  - Collector trays;
  - Feed entry devices;
  - Structural components (grids, beams, rings).

5.0 Heat-Transfer Services

The heat-transfer service in the refinery vacuum tower takes sub-cooled pumparound return liquid and condense the rising vapors. More than sufficient heat transfer takes places to return the pumparound liquid to saturated conditions. As they lose heat, the vapors condense and create the net product liquid.

Structured packing is the overwhelming choice for heat-transfer services. The dominant factor in heat transfer effectiveness is packing surface area per unit volume and relative vapor and liquid loads. Packing should be evaluated based on a volumetric heat-transfer coefficient similar to a heat exchanger. Methods based on using a number of stages from a mass-transfer based model combined with a HETP (Height Equivalent of a Theoretical Plate) are often misleading. All commercially available process simulators used in industry use mass-transfer based models for their calculations.

Both spray nozzles and gravity liquid distributors can be used in heat-transfer beds. Spray nozzle assemblies are most commonly used. They are inexpensive, able to handle a 2:1 rate range, and perform well. Fabrication should use 150-class RF flanges for all internal joints.

The great advantage of spray nozzle distributors is that they act as a good stand-alone heat-transfer device. The heat-transfer of the spray nozzle distributor is normally ignored in the heat-transfer calculation. This gives considerable conservatism in heat-transfer bed design.

Other types of distributors can be used. The most common alternate is a trough-distributor. Liquid rates in heat-transfer beds are high enough that trough distributors often require multiple parting boxes. Trough distributors do no extra heat-transfer when distributing the liquid.

6.0 De-Entrainment Services

The vacuum tower feed enters in the tower flash zone. The high-velocity feed creates small liquid droplets. The feed entry device, coupled with the lower column vapor velocity, allow the larger droplets to fall towards the tower bottom. However, the smaller droplets still entrain up the tower. At sufficiently low C-Factors (<0.18), entrainment rates are very low. Commercial units operate at much higher C-Factors. Vacuum towers include a wash bed to reduce the amount of entrainment. An ideal vacuum tower – one without entrainment – would not require a wash bed.

Both structured packing and grid are used in wash beds. Some units will use a combination of both. Combined beds have grid on the bottom and structured packing on the top.

Wash beds combine extreme process requirements and challenging operating conditions. Many wash beds have failed. The major sources of wash bed failure are coking due to insufficient wash oil or pressure surge induced damage due to water accidently getting into the operating unit.
6.1 Wash Bed Requirements

Yield economics drive wash oil rates down. Any liquid that leaves the bottom of the wash bed enters the tower bottoms. Even with stripping trays present, excess liquid leaving the bottom of the wash bed decreases gas oil yield and increases vacuum residue yield. This has a significant economic cost.

A minimum wash oil rate is required to keep the liquid residence time down. Thermal cracking results from high-temperature operation if residence time in the bed goes too high. If the wash rate gets too low, the wash oil may wet the metal surface, but not flow. This creates the conditions for thermal cracking.

Thermal cracking deposits coke in the bed. Coke in the bed decreases open area for flow. This increases vapor velocity. Higher vapor velocities carry more entrained material to the HVGO product. Higher vapor velocities also increase pressure drop, which increases flash zone pressure and decreases desired product yields. Coke deposits have significant economic costs.

6.2 Wash Bed Operation

Wash beds have higher liquid rates at the top of the bed than at the bottom of the bed. Three equipment factors tie into this;

- Fractionation performance of the bed;
- Pressured drop of the bed;
- Upstream transfer line performance.

The ideal wash bed would have zero mass-transfer efficiency and zero pressure drop while obtaining complete de-entrainment. Unfortunately, higher de-entrainment efficiency tends to have higher pressure drop and more fractionation. Open grid and low-efficiency structured packing is used to balance sufficient entrainment removal against pressure drop and fractionation.

6.2.3 Expected Dry-Out Ratios

Wash bed dry-out ratio is defined as actual volume at the top of the bed divided by actual volume at the bottom of the bed. Operating units have shown dry-out ratios as high as 15:1. The equipment factors listed, plus a variety of process reasons create these high dry-out factors. Dry-out is normally under-predicted with conventional analysis approaches. Great care needs to be taken in this area.

6.2.4 Expected Wash Bed Depth

Deeper wash beds improve de-entrainment. Deeper wash beds increase the dry-out ratio and reduce tower capacity. Current practice has wash bed depths varying from 3 ft (0.91 m) to 6 ft (1.83 m). Most units are in the 4 ft (1.21 m) to 5 ft (1.52 m range). Shorter beds (3 ft, 0.91 m) have less than one theoretical stage of efficiency but will have noticeable entrainment. Shorter beds are used when some entrainment can be tolerated. The deeper beds are used in situations when volatile metals are significant or products are entrainment sensitive. These depths are based on grid or low-efficiency structured packing use.

6.3 Minimum Wetting Values

The author’s recommended minimum wetting value for the wash bed is 0.15 US-gpm/ft² (0.37 m³/hr-m²) of distillate liquid at the bottom of the bed. This value is based on liquid volume at actual conditions and tower cross section area for the wash bed. Distillate liquid means that this is the
liquid rate at the bottom of the bed without adding any rate for entrainment to the calculation. This liquid rate is based on experience with many units over the last two decades.

6.4 Maximum Vapor Rates

No wash bed operates perfectly. Some entrainment always occurs. How much entrainment is acceptable depends upon what is being entrained and where it will go. Cleaner crudes will allow the plant to tolerate more entrainment. The maximum bed capacity is generally accepted as a C-Factor of 0.45 ft/sec. However, verified data from some units running light crude has shown successful operation at C-Factors as high as 0.50 ft/sec. This would never be recommended as a design basis. Nevertheless, if the crude is clean enough that significant entrainment can be tolerated, high C-Factor operation on light crudes is possible on some units. Success of this high-rate operation depends upon many precise details in the equipment design of the vacuum tower beyond the scope of the general discussion here. The author has not seen verified, high-quality data showing successful operation above a 0.50 ft/sec C-Factor.

8.0 Stripping Services

The bottoms liquid contains the liquid from the flashed feed entering the column. Some vacuum towers include steam stripping off the bottoms stream. Reasons for steam stripping may include recovery of light material for yield improvement, flash control of the bottoms product, and viscosity control of the bottoms product. Trays are the most common device used.

8.1 Tray Process Design and Layout

Stripping trays in this service are normally sieve trays with large-diameter holes (>= 0.75 inches, 19 mm). Occasionally conventional 0.5 inch (12.7 mm) diameter holes are used. Some units have used fixed-valves for the stripping trays, but that has few benefits and increases the risk of plugging.

Vapor rates change dramatically across each tray. It is essentially impossible to create a single tray layout that will work across the entire stripping section. The bottom tray has such a low vapor rate that the low hole area it requires to work would cause the top tray to have excessive pressure drop and flood. The top tray has such a high vapor rate that the bottom tray with that hole area would weep and have extremely low efficiency. Multiple tray layouts will be required.

Even with customized tray designs, the trays will have low efficiency. At best, tray efficiency will be 25-30%.

8.2 Tray Mechanical Design

Operating conditions subject the stripping trays to severe service conditions. Tray failure occurs routinely. The two major sources of tray failure are pressure surge due to flashing of water and upsets due to high liquid level. On many units both occur routinely. Unit startup creates most of the problems. Some units have never started up successfully with the stripping trays in place. A systems approach is needed to keep the stripping trays intact. Steps include configuration of external piping to reduce the risk of water getting to the tower in the stripping steam, reliable level measurement, sound operating procedures and mechanical upgrades to the trays.
9.0 Collectors (and Vapor Distributors)

9.2 Collector Tray Mechanical Configuration

Collector trays should have the following features;

- Fully seal-welded construction to eliminate leaks;
- No bolted openings in the tray deck;
- Access through the tray by having a riser large enough for personnel to fit through;
- Thermal expansion joints if operating at over 400°F (204°C);
- Risers configured to prevent re-entrainment of liquid that falls on the riser hats.

In addition, the slop wax collector tray should have sloped construction of a minimum of a 1 inch slope per six ft (1.4 cm per m). This reduces liquid residence time on top of the tray and encourages quick draining of condensate from the bottom of the tray. Both reduce the probability of the slop wax collector coking.

10.0 Flash Zone Distributors (Two-Phase Feeds)

Feed entry in the flash zone is the second area where recent years have seen major advances in vacuum tower technology. Feed may enter the vacuum tower either radially (aimed across the center of the tower) or tangentially (aimed along a tangent to the tower circumference). Surveys of existing units show no clear pattern. Preferences between vendors vary. The author’s analysis is that no convincing data are available the show either has consistently better performance.

If done correctly, either is acceptable. While improving an existing flash zone entry may be very attractive, the improvements should focus on the geometry of the feed line and the tower internals. Changing an existing unit to switch either way between a radial entry and a tangential entry for that purpose alone is not justified.

10.3 Modern Tangential Entries

Modern tangential entries use vanes to direct vapor into a core region of the tower. The tangential entry forms a torus channel inside the tower. The vessel wall plus vanes inside the torus provide impingement surfaces for liquid collection. The vanes are located at stepped elevations around the torus. Each vane cuts away a portion of the vapor at that point and directs it to the tower center.

10.4 Modern Radial Entries

Modern radial entries use vanes to direct vapor to both sides of the entry device. The vanes also provide an impingement surface for liquid collection. The liquid flows sideways along the vane and falls off the end. The leading edge of the vanes move closer as the feed crosses the tower. Each vane cuts away a portion of the vapor at that point and directs it to the tower sides.

11. Structural Components

Structural components including gratings, beams, rings and hold down rods are used to support internals and keep them in place. Gratings are used to support packed beds. Depending upon spans and bed weights, beams may be required to give sufficient support. Beams may also be required to support the weight of liquid full collector trays.

Structured packing supports typically use a subway grating for bed support. The subway grating is installed upon required beams. The subway grating has minimal cross section area reduction.
However, in large units, the beams may significantly reduce the cross flow area of the tower. This must be accounted for in determining cross section area for load calculations. Alternatively, beam designs can allow for flow through the beam to reduce this affect.

Rings are often used to support the outer edge of the packing support. Again, when pushing to the limits of tower capacity, the cross-flow area reduction of the support ring may be important. Support rings that allow for minimum area reduction are available.

Packing hold-down grids should always be used. Packing can move under dynamic loads or pressure surges due to water in the unit. Moving packing hammers other internals. Packing shifts may also open spaces that allow vapor or liquid to bypass the bed.

Through bolting is one technique of holding beds in place. This is often used in wash beds of units that have a demonstrated history of equipment damage from water pressure surges. Conventional through bolts extend all the way through the packed bed and lock the bed to the support structure. J-bolts are hook-type bolts that are used for the same purpose with grids.

12. Other Equipment

12.2 Wire Mesh Mist Eliminators

Wire mesh mist eliminators are a hold-over from vacuum towers that used bubble-cap trays. Bubble-cap trays generate significant quantities of small droplets that would entrain. Modern vacuum towers should never have wire mesh installed anywhere except at the overhead vapor exit.

Even at the overhead vapor outlet, the wire mesh is not recommended. Alternates to reduce carryover to the vacuum system are discussed along with heat-transfer service distributors.

14. Extended Abstract Note

The extended abstract was prepared from a full version of the paper. Original header section numbering has been kept in the extended abstract.