5.11.2 Packing

A variety of packings differing in shape, size and performance are available. These may be classified into three categories: (i) random or dumped packings, (ii) structured packings, and (iii) grid packings. Random packings are just dumped into the shell to give the packing pieces a random orientation. Structured packings are stacked in the shell to take the shape of a packed bed.

Characteristics of tower packings

Besides low cost, the desirable characteristics of packings are described below (Kister, 1992).

(a) *A large surface area:* Interfacial area of contact between the gas and the liquid is created in a packed bed by spreading of the liquid on the surface of the packing. Smaller packings offer a larger area per unit packed volume, but the pressure drop per unit bed height becomes more.

(b) *Uniform flow of the gas and the liquid:* The packed bed must have a uniform voidage so that a uniform flow of the gas and of the liquid occurs. The shape of the packing should be such that no stagnant pocket of liquid is created in the bed. A stagnant liquid pool is not effective for mass transfer.

(c) *Void volume:* A packed bed should have a high fractional voidage so as to keep the pressure drop low.

(d) *Mechanical strength:* The packing material should have sufficient mechanical strength so that it does not break or deform during filling or during operation under the weight of the bed.

(e) *Fouling resistance:* Fouling or deposition of solid or sediment within the bed is detrimental to good tower operation. Bigger packings are less susceptible to fouling. Also, the packings should not trap fine solid particles that may be present in the liquid.

Types of tower packings

Tower packings are made of ceramics, metals or plastics. Several innovations in the design of tower packings took place in the last quarter of the twentieth century and the process is continuing. Kister (1992) and Larson and Kister (1997) identified three *generations* of the evolutionary process (Table 5.6) of the *random packing.*

Table 5.6 Classifications of tower packings

- Random
  - *First generation*: Raschig ring, Lessing ring, Cross-partition ring, Berl saddle, Spiral ring.
  - *Second generation*: Pall ring (plastic and metal), and its modified versions (like Flexiring, Hy-pac, etc.), intalox saddle and its modifications, etc.
  - *Third generation*: IMPT (Norton), CMR (Norton, Glitsch), Nutter ring, Jaeger Tripac, Koch Flexisaddle, Flexi-max, Norpac, Hiflow, etc.
- Structured (see Tables 5.7, 5.8)
- Grid

(a) ***First generation random packings*** (1907 to mid-1950s): These included three types of packings—Raschig rings, Lessing rings and other modifications of the Raschig ring and Berl saddles (Figure 5.20). These are mostly packed randomly; 'stacked' packings are used in only a few cases.

Raschig ring: This is the oldest type of tower packing introduced by the German chemist F. Raschig in 1907. It is a hollow cylinder having a length equal to its outer diameter. The size of the Raschig ring ranges from ¼ inch to 4 inches. These rings are made of ceramic materials (unglazed porcelain), metals or plastics (e.g. high-density polyethylene, HDPE). Metal or plastic rings are made by cutting tubes of a suitable size. The Raschig ring is probably the most rugged packing and can be used even when a severe bumping or vibrating condition may occur. Other members of the Raschig ring family are: (i) 'Lessing ring', which is similar to the Raschig ring except that it has a partition along the axis of the ring. The partition increases the surface area but the advantage is rather small in practice. This packing has not been quite popular. (ii) The 'cross-partition ring' that has two partitions instead of one in a Lessing ring. (iii) The ceramic 'spiral ring' that has an internal helix which creates internal whirl of the gas and of the liquid and enhances the rate of mass transfer. The latter two types are sometimes stacked in one or two layers on the support grid of a randomly packed tower. Although Raschig rings are still in use, the other variations of them are rarely used.

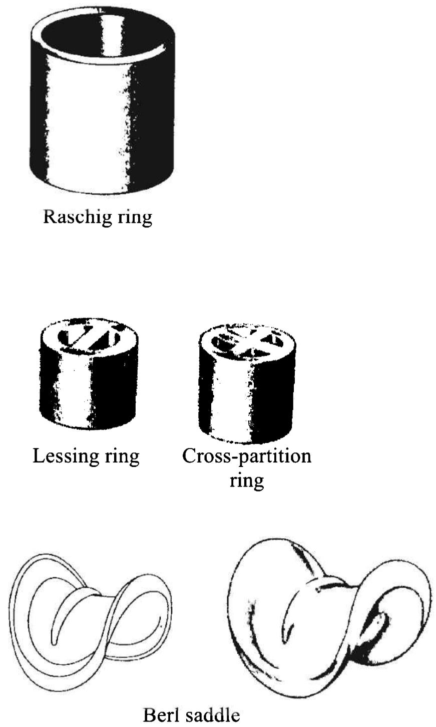


Figure 5.20 First generation random packings.

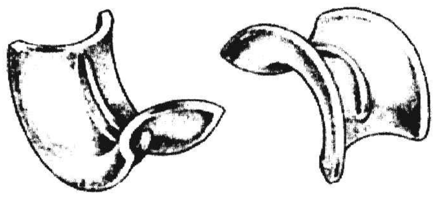
Berl saddle: The Berl saddle (Figure 5.20) is the first modern packing developed in the late 1930s. It is so called because it has the shape of a saddle. A packed bed of Berl saddles has a larger specific surface area (i.e. surface area per unit packed volume) and a smaller voidage than the Raschig ring. Compared to the Raschig ring, the pressure drop is substantially less because of its 'aerodynamic shape'. It has a rib on one surface that prevents possible overlapping of the surfaces of two adjacent pieces. Berl saddles offer higher capacity and a better performance than the Raschig rings but are more expensive.

(b) ***Second generation random packings*** (mid-1950s to mid-1970s): The 'Intalox saddle' ('Intalox' is a trademark of Norton) may be considered to be the first member of the second generation random packing developed by the Norton Chemical Products Corporation in the early 1950s. It is an improved version of the Berl saddle and offers lesser 'form friction' resistance to gas flow. Because of its particular shape [Figure 5.21(a)] two adjacent pieces of the packing do not 'nest' and hence a stagnant pool of liquid is not created between them. The area of the packing is almost fully utilized for effective contact and mass transfer between the gas and the liquid phases. Like the Berl saddle, it offers a larger specific interfacial area and a smaller pressure drop compared to the Rasching ring. Nevertheless, Intalox saddles are better packings than the Berl saddles. Koch-Glitsch[†] offers a similar ceramic packing under the trade name 'Flexisaddle'. The

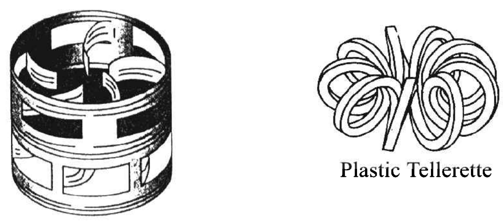
[†] Koch Engineering Company and Glitsch, Inc., merged to form Koch-Glitsch in the late1990s.

Intalox saddle and its modified varieties (one important type from the erstwhile Norton Corp. is called 'Super Intalox saddle') are of ceramic or plastic make. The smooth edges of the Intalox saddle are scalloped and holes inserted to make the super Intalox. This design promotes quick drainage of the liquid, eliminates stagnant pockets and provides more open area, higher capacity and efficiency. 'Intalox snowflakes', introduced by the Norton Corp. in 1987, is a plastic packing of unique shape having a large number of liquid drip points, causing continuous renewal of the liquid surface and superior mass transfer performance.

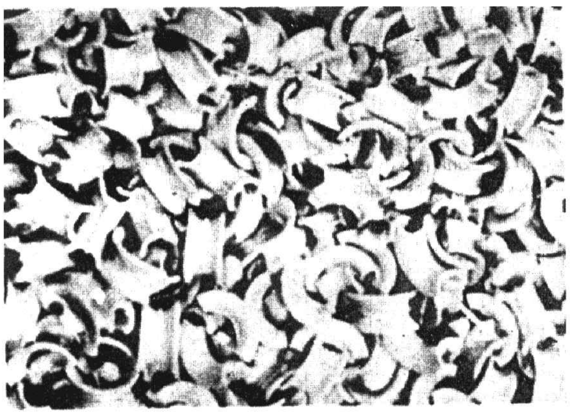
Pall rings: The Pall ring and its modifications evolved from the Raschig ring. It is made by cutting windows on the wall of a metal Raschig ring and bending the window tongues inwards. While a bed of saddles offers reduced 'form friction' or drag because of the aerodynamic shape, Pall rings [Figure 5.21(b), (d), (e), (f)] do so by allowing 'through flow'



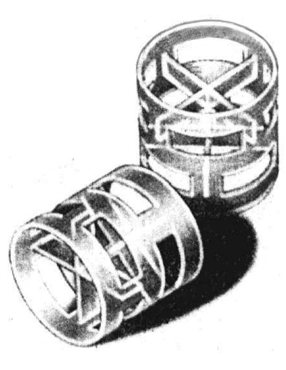
(a) Intalox saddle



(b) Pall ring



(c) Dumped intalox saddles



(d) Plastic pall ring (Glitsch)

(e) Metal 'Flexiring' (Koch Engg.)

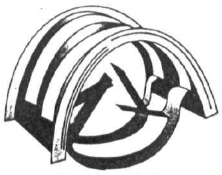
(f) Norton 'Hy-Pak' ring (metal).

Figure 5.21 Second generation random packings.

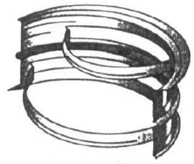
of the gas, because direct passages on the wall are available. Since the interior surface is much more accessible to gas and liquid flow, the capacity and efficiency of the bed are enhanced. Similar packings are marketed by other companies under different trade names (for example, 'Flexiring' of Koch Engg.). Plastic Pall rings are also available (Norton Company, Koch-Glitsh, Jaeger Products, etc.). The metal 'Hy-Pak Tower Packing' of the Norton Corp. [Figure 5.21(f)], a slightly modified version of the Pall ring, has two bent tongues in each window and is claimed to have better efficiency. Ceramic Pall rings, which are Raschig rings with a few windows on the wall, have not been very popular.

(c) ***Third generation random packings*** (mid-1970s-): A pretty large number of metal and plastic tower packings have been developed since mid-seventies that offer improved performance in terms of lower pressure drop, less weight, larger interfacial area and lesser liquid retention in the bed. Many of these packings evolved from the intalox saddle. The 'Intalox Metal Tower Packing' (IMTP), a random packing developed by the Norton Corp., *combines* the high void volume and even distribution of surface area of a Pall ring and the aerodynamic shape of the Intalox saddle. The 'Fleximax'† is an open saddle type packing from Koch-Glitsch. 'Nutter rings' have somewhat similar characteristics and are available in both metal and plastic. A few other types are also shown in Figure 5.22. These are collectively called the third generation random packings (Kister, 1992).

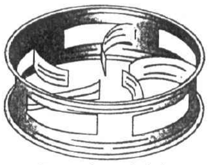
Several third generation random packings have been the offshoots of the Pall ring (Figure 5.22). The Cascade Mini-Ring (CMR) is similar to the Pall ring but has a height-to-diameter ratio



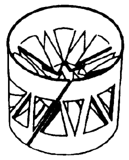
Intalox metal tower packing (IMTP)



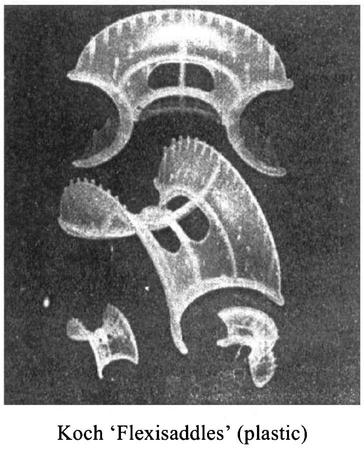
Nutter ring



Cascade Miniring



Metal Bialecki ring

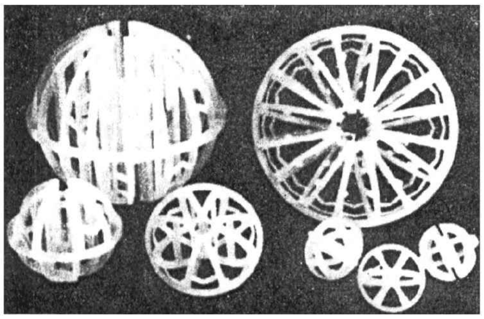


Koch 'Flexisaddles' (plastic)

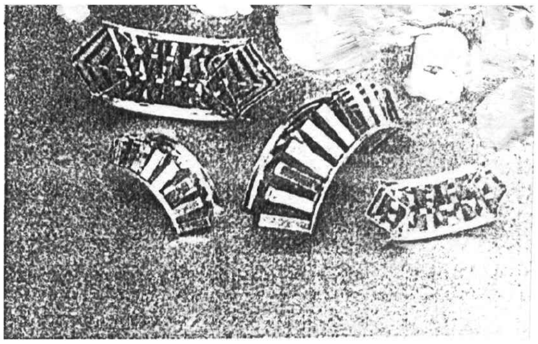
Cascade Minirings (Jaeger)

Figure 5.22 (*Contd.*)

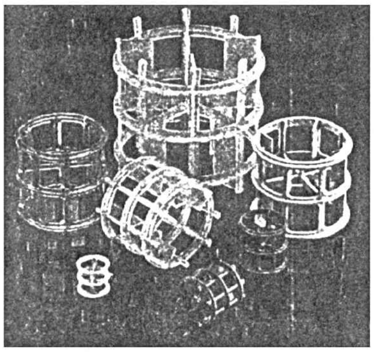
† Koch-Glitsch chooses to call *Fleximax* a 'fourth generation packing'.



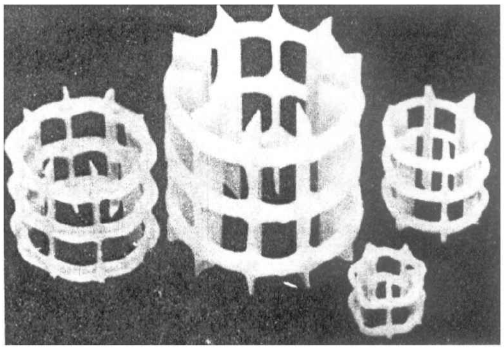
Jaeger 'Tri-packs' high performance packing made of corrosion-resistant plastic



Kock 'Fleximax' tower packing



Hiflow ring (Rauschert Ind.)



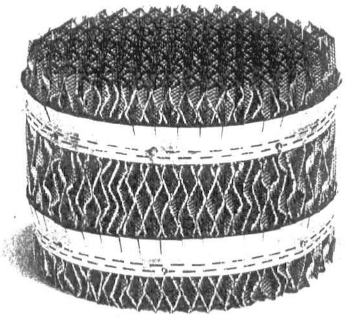
Nor-Pac, Plastic (NSW Corp.)

Figure 5.22 Several third generation random packings (IMTP: Norton Co; CMR: Norton Co, Glitsch).

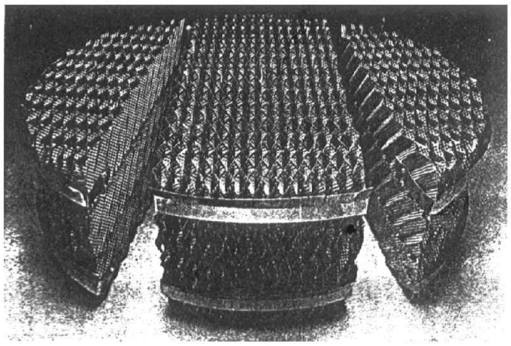
(this is sometimes called the 'aspect ratio') of 1:3 compared to 1:1 of the latter. Because of low height, such a packing element has a lower centre of gravity and therefore tends to orient with the circular open end facing the vapour flow. This reduces friction and enhances the mass transfer coefficient and effective surface area. The 'Chempak' or 'Levapak' ring is made by cutting the Pall ring in two halves, exposing the tongues and promoting better performance. The Jaeger 'Tri-Packs' (metal or plastic) resembles the Pall ring but has a spherical shape (Figure 5.22). This packing offers more void volume and better distribution of surface area. It also prevents interlocking of the pieces in the bed. HcKp (from Koch), NOR PAC (from Nutter Engineering), LANPAC (from Lantec Products) are a few other third generation random packings.

Structured packings

Structured packings have emerged as the formidable competitor of random packings since the 1980s (Helling and DesJardin, 1994; Bennett and Kovac, 2000). These are made from woven wire mesh or corrugated metal or plastic sheet. Their major advantages are low gas pressure drop (because of 'through flow' of the gas) and improved capacity and efficiency. The first structured packing, called *Panapak*, made from thin metal strips to form a honeycomb-like structure did not gain much popularity because of severe maldistribution of liquid. Since the late 1970s and the early 1980s, Glitsch Inc., Sulzer and Nutter Engineering came up with acceptable high efficiency structured packings made of corrugated metal sheets or wire mesh (Figure 5.23).

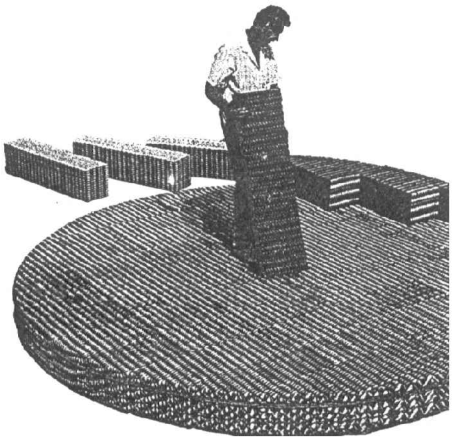


(a)

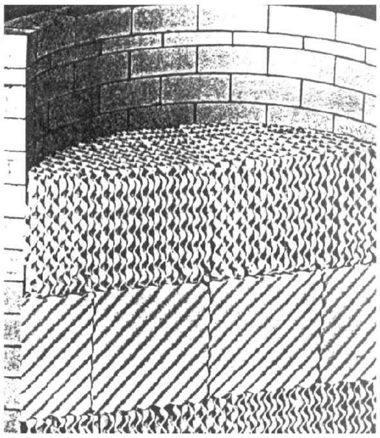


(b)

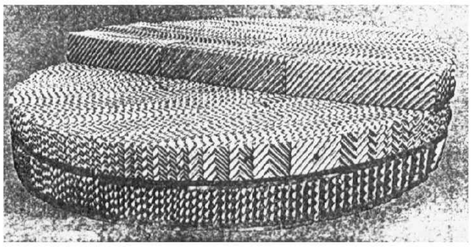
Intalox high performance corrugated structured packing (made from thin metal sheets).



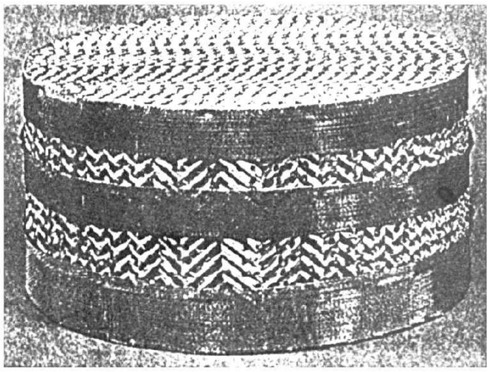
(c) The same as Figure 5.23(a) and (b).



(d) 'Flexeramic' corrugated structured packing (Koch Engg.).



(e) 'Montz B1' Structured packing (Nutter Engg. Corporation).



(f) Sulzer wire-gauge packing CY.

Figure 5.23 A few common high performance structured packings made from thin metal sheets or wire gauge.

Corrugated metal sheet structured packing: There are quite a few tower packings of this category. These are fabricated from thin corrugated (or crimped) metal sheets. The surface of a sheet is often made embossed, textured or grooved to promote mixing and turbulence in the falling liquid film and thereby to increase the mass transfer coefficient and efficiency.

The flow channel cross-section and flow channel arrangement in a common structured packing is shown in Figure 5.24. A bunch of corrugated sheets are arranged parallelly, keeping a suitable gap between the adjacent members to make a packing piece. A number of such pieces are arranged and stacked one after another. A piece of packing above is rotated at a certain angle relative to the piece immediately below it. The height of a piece is typically 8 to 12 inches. The corrugation angle of the sheets varies from 28° to 45° (Fair and Bravo, 1990; Olujic et al., 2001). Perforations are sometimes made on the sheets to provide channels of communication between the two surfaces of a corrugated sheet and to improve wetting of the surfaces. A larger corrugation angle increases the capacity in terms of the liquid load but reduces the mass transfer efficiency.

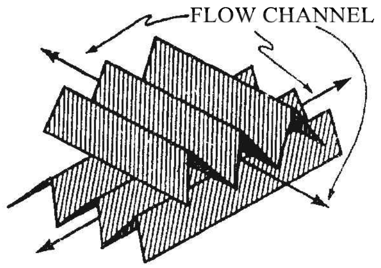


Figure 5.24 Flow channel arrangement in a corrugated structured packing (Fair and Bravo, 1990).

Wire mesh structured packings: Sulzer supply three types of such packing marked AX, BX and CY. The packing elements are made of corrugated layers of wire mesh. Sulzer packing type CY shown in Figure 5.23(f) has a surface area of about 200 ft^2/ft^3. Similar packings are marketed by Glitsch under the trade name *Gempak*, and by Norton Corp under the name 'Intalox High-Performance Wire Gauge Packing'. Glitsch also developed *Goodloe* for which the knitted wire-mesh is used. A cylindrical tube made by knitting multi-filament wires is flattened into a ribbon and then made into a packing by corrugation. It has a surface area above 550 ft^2/ft^3. *Montz A* packing (Nutter Engineering) is made from perforated wire mesh sheets with a specially contoured corrugation [Figure 5.23(e)]. The surface area is about 150 ft^2/ft^3. This packing is similar to the Sulzer wire mesh packing. The characteristics of a few structured packings are given in Table 5.7.

Table 5.7 Characteristics of a few structured packings

Structured packing	*Material and surface*	*Crimp angle*	*Area*
Mellapak	Metals, plastics; grooved and perforated	45° or 60°	About 250 m^2/m^3
Flexipak	Similar to Mellapak	–	
Gempak	Smooth or lanced	45°	
Montz	Metals, plastics; embossed	Sinusoidal	
MAX-PAC	Metals; smooth; W-shaped perforations	Sharp crimp angle	

Although developed in the late 1970s, the structured packings made visible inroads to separation technology in the late 1980s. The first major application was in air separation columns (Parkinson and Ondrey, 1997). The higher initial cost of such packings is amply compensated by the lesser operating costs because of lesser pressure drop across the bed. As a result, these packings have been very popular for use in vacuum distillation columns. The packings have high efficiency (low 'HETP') as well. Also, the well-defined geometric shape, particularly of those made from corrugated sheets, makes them amenable to theoretical analysis, modelling and scale-up (Fair and Sticklemayer, 1998). Now, the structured packings are being used for near-atmospheric services as well (Bravo, 1997).

Another class of packings, called 'grid packings', have been in use since long for high gas/vapour capacities at a low pressure drop. The more common structured and metal grid packings and their suppliers are listed in Table 5.8 (Bravo, 1997, 1998). Modern grid packings are also supplied by these companies (see Figure 5.25).

Table 5.8 Common structured packings

Supplier	*Structured packing*	*Metal grid packing*
Sulzer Chemtech	Mellapak series	Mellagrid series
Koch Engineering	Flexipak series	Flexigrid series
Glitsch Inc.	Gempak series	C-Grid and EF-25 Grid series
Nutter Engineering Co.	Montz series	Snap Grid series
Jaeger Products	MaxPak series	

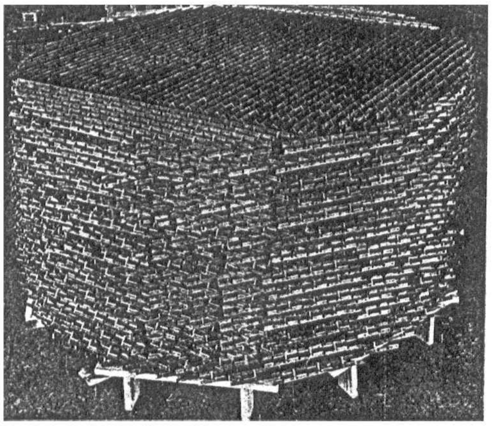


Figure 5.25 Glitsch EF-25A grid packing made of open area metal or plastic panels.

Materials for tower packings

Common materials for tower packings are ceramic, metals, and plastics. The selection of a material for fabrication of tower packings depends upon factors like ease of fabrication, mechanical strength, corrosion resistance, wetability, ease of cleaning, and cost. Ceramic packings declined in popularity since the advent of plastic packings. Ceramic packings are preferred for highly corrosive services (for example, the air-drying tower and SO_3 absorption tower in a H_2SO_4 plant) and also for operation at elevated temperatures. However, these have limited shapes (normally rings and saddles only), are prone to breakage, and require more 'downtime' for filling, removal and cleaning. Metal random packings offer higher capacity, efficiency and turndown ratio because of a smaller wall thickness and more open area. For example, 1 inch ceramic Raschig rings have a wall thickness of ⅛ inch and a void volume of 74%, and weight 27 lb per ft^3 packed volume; the same size carbon steel packings have wall thickness of $\frac{1}{32}$ inch, voidage 92%, and weight 40 lb per ft^3. Metal packings are unbreakable and have higher compression resistance but have less wettability than that of ceramic rings. For corrosive services, a suitable type of stainless steel is used. Plastic packings are cheap, unbreakable, light, and corrosion-resistance. Common materials, are polyethylene, polypropylene, PVC, and poly-vinylidine fluoride. Plastic packings may be made into a large number of shapes. It is rather easy to fill them and clean them in situ by water or even steam, thus reducing the downtime to a tenth of that for ceramic packings. The disadvantages of plastics packings are: poor wettability, brittleness at low temperature or on aging, tendency to degrade in an oxidative environment or when exposed to UV. Plastic packings are more expensive than the ceramic packings.

5.11.3 The Packing Support and the Gas Distributor

The support plate or grid has three functions: (i) it supports the weight of the packing and the liquid held up in the packing during operation; (ii) it allows the gas to flow through it and to get distributed (uniform gas distribution at the support is extremely important for satisfactory performance of a packed bed); and (iii) it allows the liquid to leave the bed. There should also be an uninterrupted dripping of liquid through the support plate. Even small liquid pockets built up on the support plate badly affect the gas distribution and hence the tower performance.

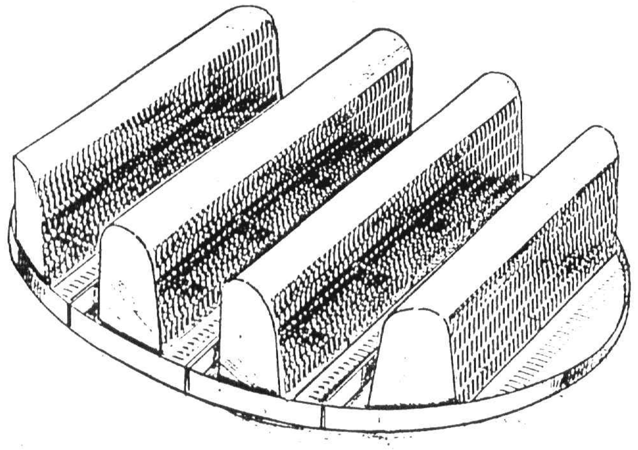
The packing support ring is bolted or clamped to another ring which is welded to the wall. As such the support plate should be as open as possible. The open area should be above 70%, preferably above 85%. The gas pressure drop across the plate is small. A few types of support grids are described below. The selection of a support depends upon a number of factors including the tower diameter, the height of the packing, the packing type and size, and the mass flow rate ($kg/h{\cdot}m^2$) of the gas and of the liquid stream.

The gas injection grid: This is a commonly used packing support [Figure 5.26(a)]. A gas injection grid allows the gas and the liquid to flow through separate openings—the liquid flows through the openings at the floor of the support, and the gas flows through the upper openings. It has an effective area of 80% to more than 100% of the tower cross-section. It is also known as multiple beam support.

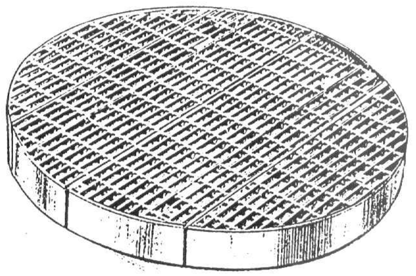
The grid support: This type of design is shown in Figure 5.26(b). The structural elements of the grid remain on two different planes. A free area of 95% or more is attainable. Such support grids are suitable for reasonably clean liquids and can handle moderate-to-large vapour rates. Also, these are suitable for larger diameter columns.

The "Cap-type" support plate: Such a support is shown in Figure 5.26(c). This is a very good design but is more expensive. It is often used in small diameter columns.

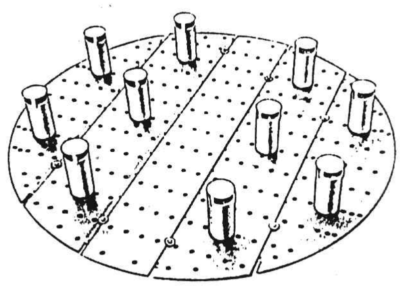
A bad gas distributor creates channelling of the gas through the bed. Channelling means that the gas flows preferably through certain regions of the bed. This leads to uneven gas–liquid contact and unsatisfactory column performance. Channelling also occurs if the bed is not uniformly packed.



(a) Gas injection packing support plate (Koch Engineering).



(b) Grid-type support plate (Koch).



(c) Orifice support plate-cum-liquid redistributor.

Figure 5.26 Packing support plate-cum-gas distributor.

5.11.4 Liquid Distribution and Redistribution

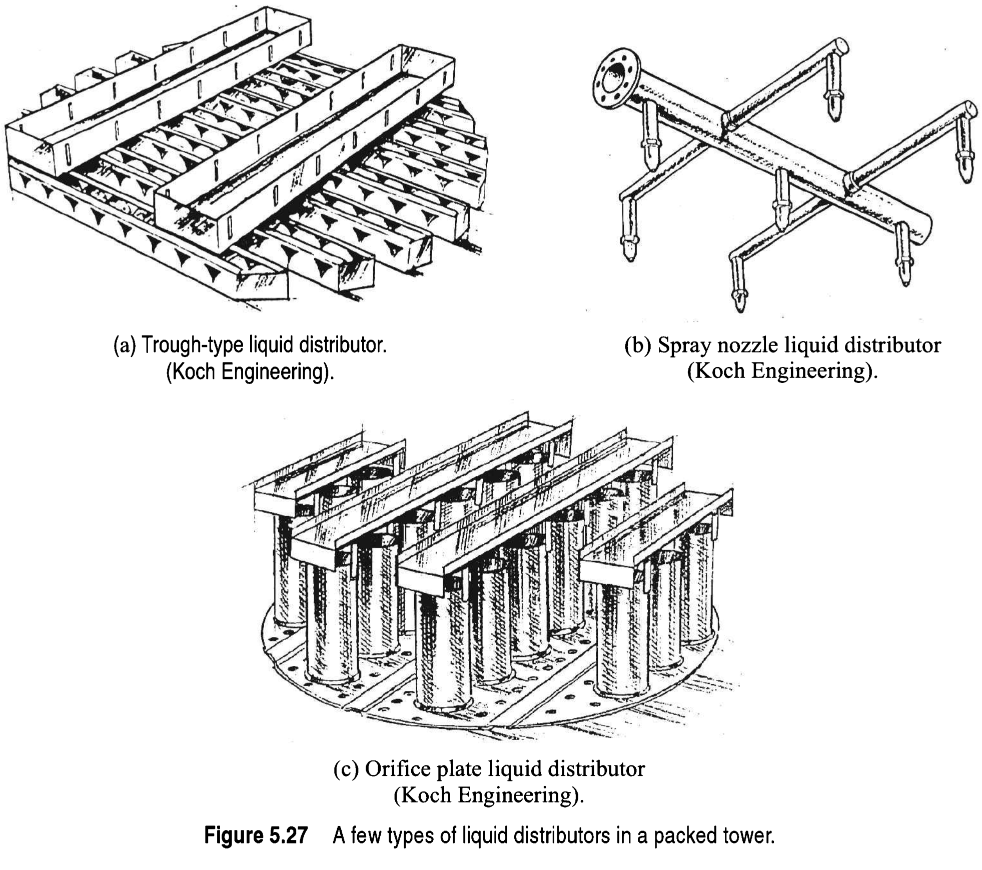
Proper distribution of the feed liquid over the bed is essential for satisfactory performance of a packed tower. Otherwise the bed will not be uniformly wetted and there will not be good gas–liquid contact. Ideally, the liquid should be distributed at an infinite number of points on the bed. In practice, a liquid distributor feeds the bed at a pretty large number of points (6–10 points/ft^2; Klemus and Bonilla, 1995) at equal rates. The more common liquid distributors are described below. The choice of a liquid distributor depends upon (i) the liquid flow rate, (ii) the plugging or fouling tendency, and (iii) the turndown ratio.

V-*notched channel distributor:* This type of distributor [Figure 5.27(a)] is widely used in columns of diameter 3 ft and above. The liquid is fed to a main trough provided with holes at the bottom or slots on the sides. It flows through the orifices or slots to a set of parallel troughs or channels below the main trough. V-notches on the sides of these lower troughs allow the liquid to flow into the packed bed. Levelling of the troughs is very important to ensure equal overflow through the weirs. This type of distributor offers a high turndown ratio because of the variable flow area available. It is also suitable for a liquid having a plugging tendency or having a little suspended solids.

Spray channel distributor: This is another commonly used liquid distributor [Figure 5.27(b)]. It has a simple construction. The feed liquid enters the distributor through a central pipe and comes out through a number of nozzles. This type of distributor can be plunged below a small depth of packing so that the thin layer of 'dry packing' above the distributor acts as a mist eliminator.

Orifice plate liquid distributor: In this type of distributor, the liquid is fed to a number of channels. The liquid flows down to the distribution plate [Figure 5.27(c)] having a large number of orifices. The gas flows up through a number of tubes without interfering with the liquid flow.

Liquid redistribution: A randomly packed bed is not truly random. Local non-homogeneities or variation in voidage and open area for gas flow occur. Although the overall direction of flow of the liquid is towards the bottom, local lateral flow occurs, depending upon the orientation of a piece of packing. But the liquid that reaches the wall of the tower rarely gets dispersed in the lateral direction again. Further, the liquid tends to flow along the wall because it is a continuous surface and because the voidage near the wall is always larger than that in the bulk. This is called *channelling of the liquid.* Such maldistribution is detrimental to a good gas–liquid contact. It is, therefore, necessary to collect the liquid from the wall region and to distribute it over the bed again. A liquid redistributor (Figure 5.28) does this job.



(a) Trough-type liquid distributor. (Koch Engineering).

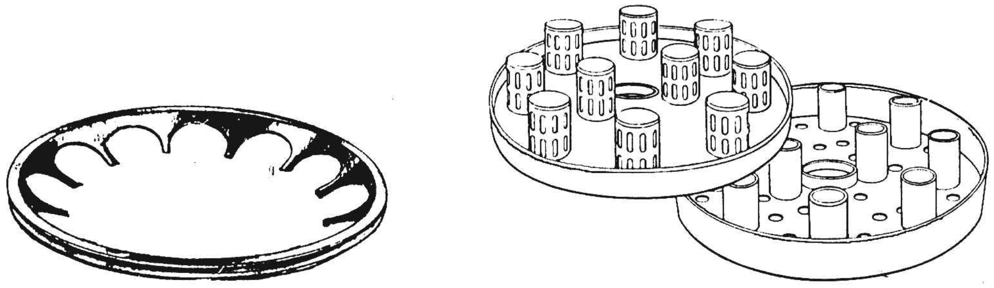
(b) Spray nozzle liquid distributor (Koch Engineering).

(c) Orifice plate liquid distributor (Koch Engineering).

Figure 5.27 A few types of liquid distributors in a packed tower.

For towers packed with Raschig rings, redistribution becomes necessary after a bed depth of 3 to 6 times the tower diameter; for a saddle-packed tower, it is 5 to 10 tower diameters. Also, the Raschig ring packing may have a depth of 10 to 15 ft per section. The depth may be 12 to 20 ft with saddle packing. This, however, depends upon the bed diameter.

For small towers of diameter 18 inches or less, a wall-wiper type distributor is popular [Figure 5.28(a)]. The wall wiper collects liquid near the wall and directs it to the central region. A packing support-cum-liquid redistributor is shown in Figure 5.28(b).



(a) (b)

Figure 5.28 (a) "Rosette" wall wiper, and (b) combination of support plate and liquid distributor.

Uniform flow of the liquid down the packing surface is an ideal condition. However, maldistribution of liquid that occurs to a varying extent almost unavoidably affects mass transfer efficiency of a column. The issue has been addressed in the literature (Perry et al., 1990; Bonilla, 1993; Klemas and Bonilla, 1995; Killat and Rey, 1996).

5.11.5 Packing Hold-down Plate or Bed Limiter

A sudden surge in the gas flow rate in a tower may physically lift the packing and may even fluidize a layer of packing at the top. This may break the ceramic packings besides causing maldistribution of the fluids. A bed of plastic packing is more prone to be lifted. It is a common practice to provide a 'packing hold-down plate' or 'bed limiter' at the top of the bed. The hold-down plate is made of wire-mesh with weighted rib support and has nearly 100% open area (Figure 5.29). A hold-down plate may be in place under its own weight. It may also have welded lugs that can move through narrow guiding slots along the wall, thus allowing only up and down movement of the device.

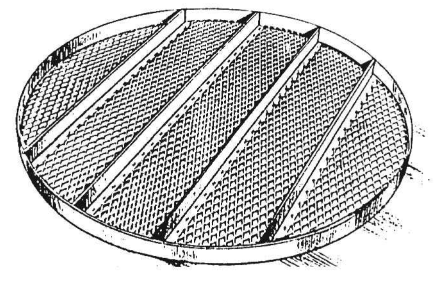


Figure 5.29 Packing 'hold-down plate' or 'bed limiter'.

5.11.6 Demister or Entrainment Eliminator

A 'demister', made of a wire-mesh or a thin metal sheet, is often placed below the gas exit nozzle to remove the entrained liquid droplets (Figure 5.30). Sometimes, a layer of packing is put above the liquid distributor. This layer, called 'dry packing', acts as an entrainment eliminator.

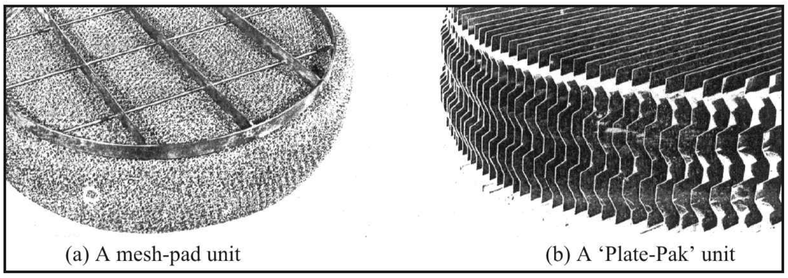


Figure 5.30 Two types of mist eliminators or demisters (*Courtesy:* ACS Industries).

5.11.7 Procedure of Packing a Tower

It is not advisable to pack a tower by dropping the packings into the tower from the top. Ceramic packing may break if dumped from above. Also the packings may not get spread uniformly; they may form a heap at the centre. A ring-type packing may roll down the heap and get a preferential horizontal orientation. There are a few common techniques (Figure 5.31) of installation of random packings. In the 'wet packing technique', popular with ceramic packings, the tower is filled with water or a suitable liquid and the packing is dumped into it. Plastic packings cannot be filled in this way because they will float in the liquid. 'Dry packing' may be done by lowering the packing in a wire bucket that is led into the column through a manhole (Figure 5.31). The chute-and-sock method is also used (this technique is very useful for loading a solid catalyst in a reactor).

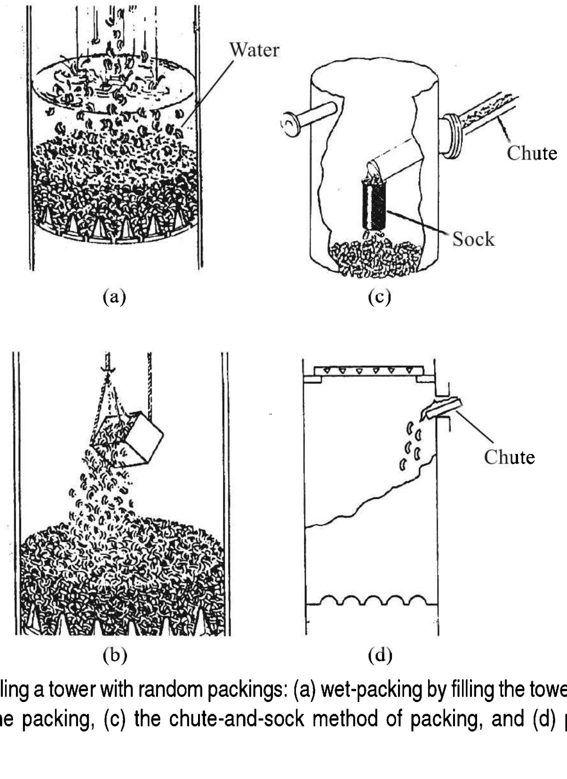


Figure 5.31 Techniques of filling a tower with random packings: (a) wet-packing by filling the tower with water, (b) dry-packing by lowering buckets filled with the packing, (c) the chute-and-sock method of packing, and (d) packing through a chute only (Chen, 1984).

On rare occasions, a random packing like the Raschig ring is stacked in a column in layers. The flow channels in such a bed are regular and the gas pressure drop becomes less as a result. Structured packings are made in pieces to fit a column of given diameter and are stacked in an appropriate way.

5.12 FLOODING IN A PACKED TOWER

A knowledge of the hydrodynamic and mass transfer characteristics of a packed tower such as the influence of the flow rate of the gas and of the liquid on pressure drop, liquid holdup and the gas- and the liquid-phase mass transfer coefficients in the bed is essential for the design of such a device for a given service. The more important hydrodynamic characteristics are discussed below.

5.12.1 Bed Pressure Drop and the Phenomena of Loading and Flooding

The liquid distributed on the top of a packed bed trickles down by gravity. Flow of the gas is pressure-driven and the pressure is generated by a blower or a compressor. The gas undergoes pressure drop as it flows through the bed because of (i) both skin friction[†] and form friction, (ii) frequent changes in the flow direction, and (iii) expansion and contraction. Maximum area for flow of the gas is available if the packing is dry, i.e. if there is *no* liquid throughput. But when a liquid flows through the bed, a part of the open space of the bed is occupied by the liquid (called 'liquid holdup' in the bed) and the area available for gas flow decreases. This is why the pressure drop of the gas increases with increasing liquid throughput. Typical gas flow rate vs. pressure drop curves on the log-log scale for a dry bed (no liquid flow) and for two constant liquid rates are qualitatively shown in Figure 5.32. The plot is linear for a dry bed. For an irrigated bed, such a curve is nearly linear with a slope of about 2 in the lower region (i.e. ΔP varies nearly as the square of gas rate). The slope of the straight section, however, decreases slightly at higher liquid rates. If the gas rate is increased at a constant liquid rate, the drag of the gas impedes the downward liquid velocity. The liquid holdup in the bed increases as a result. This steady increase in the pressure drop continues till the point B (Figure 5.32) is reached. At the point B and beyond, the upflowing gas interferes strongly with the draining liquid. Over the region B–C, accumulation or 'loading' of the liquid starts. This region is called the 'loading region'. The point C is called the point of 'incipient flooding'.

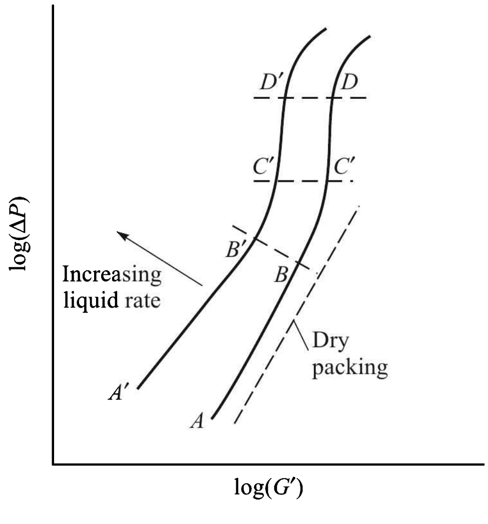


Figure 5.32 Typical pressure drop characteristics of a packed tower (qualitative).

[†] For flow past a piece of packing of 'aerodynamic design' such as saddles, the skin friction component prevails and hence the pressure drop remains low.

If the gas flow rate is further increased, the liquid accumulation rate increases very sharply. Liquid accumulates more in the upper region of the bed almost preventing the flow of gas. This phenomenon is called 'flooding'. The bed becomes 'flooded' (point *D*) when the voids in the bed become full of liquid and the liquid becomes the continuous phase — a case of 'phase inversion'. A number of definitions of flooding (more than ten!) have been put forward based on one or more of the phenomena that precede or follow flooding (Silvey and Keller, 1966; Kister, 1992; Piche et al., 2001). A widely accepted definition, suggested by Bravo and Fair (see Kister, 1992), runs as follows: "It is a region of rapidly increasing pressure drop with simultaneous loss of mass transfer efficiency." The visual and physical symptoms of flooding are: (i) accumulation of a layer of liquid at the top of the bed, (ii) a sharp rise in pressure drop, (iii) a sharp rise in liquid holdup in the bed, and (iv) a sharp fall in mass transfer efficiency (this will be discussed later).

While the operation of the column becomes very unstable over the region *CD* and the mass transfer efficiency drops significantly, some researchers have reported a reasonably stable operation beyond the point *D*. This is because beyond the point *D*, the column operates like a 'bubble column with gas–liquid upflow'.

5.12.2 Prediction of Pressure Drop and Flooding

Prediction of the flooding point and pressure drop is essential in connection with the design of packed towers. Charts, correlations and theoretical models have been proposed for this purpose. These have been thoroughly reviewed (Kister, 1992; Billet, 1995; Strigle, 1994; Piche et al., 2001). The initial significant attempt to correlate flooding data was made by Sherwood et al. (1938). Every packing has its own geometrical and surface characteristics. Pressure drop per unit bed height as well as the flooding characteristics are also different for individual packings even when all other parameters including 'nominal packing size' remain the same. However, it is not very realistic to work out separate correlations for pressure drop (and for mass transfer) for packings of different types and sizes. Instead efforts were made to develop a 'generalized pressure drop correlation' (GPDC) that would be applicable to all kinds of random packings. The idea of a GPDC was first introduced by Leva (1954). The major variables and parameters that determine the pressure drop and flooding characteristics are: (i) the properties (density, viscosity and surface tension) of the fluids and (ii) the packing type and its features (size, voidage and surface area and surface properties). A number of charts and correlations have been proposed by the US School (led by Leva, Eckert, Strigle, and Kister, to name a few; see Kister, 1992) during the last fifty years. A second group of charts and correlations have been proposed by the German School (led by Mersman, Stichlmair, Billet and others; see Billet, 1995). Some of the correlations have a semi-theoretical basis and include adjustable constants specific to a group of packing. Recently, Piche et al. (2001) reviewed all important correlations proposed for the flooding point coming from both US and German Schools. These researchers also proposed a new correlation developed by using artificial neural network (ANN) technique to 1019 data sets reported by different workers.

The GPDCs proposed by Eckert (1975 and before) of the erstwhile Norton Company[†] have been widely used for packed tower design. The 1970-version (Figure 5.33) gives a number of

[†] The Norton Corp. (formerly U.S. Stoneware) was acquired by Saint-Gobain in 1997 with the new name Saint-Gobain Norpro Corporation.

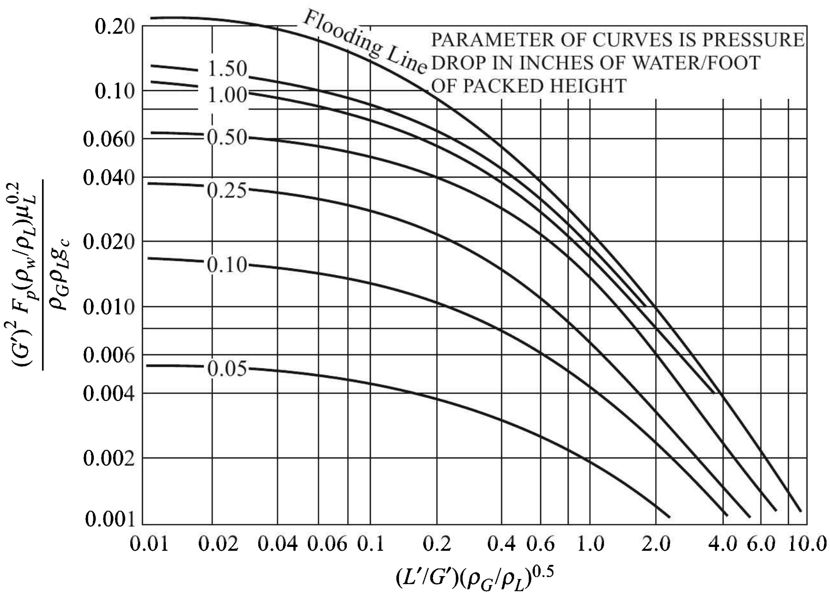


Figure 5.33 Generalized pressure drop correlation (GPDC) of Eckert (1970).

constant pressure drop curves and a flooding curve. The units of different quantities are given in Section 5.12.6. It works well with most first generation packings but not for several second generation packings and smaller modern packings. Eckert's 1975 version (not shown here) omitted the flooding curve because such a curve always has a doubtful accuracy. For first generation packings, the 'packing factor' is high (generally above 60 ft^{-1}, Section 5.12.3) and the pressure drop is $\Delta P/L \geq 2$ inches of water per foot packed height at 'incipient' flooding. Eckert's chart was further refined by Strigle (1994) using a data bank of 4500 pressure drop measurements on beds having different types and sizes of packings and using different liquids and gases. The Strigle's version† (Figure 5.34) is now most popular for packed tower design (Larson and Kister, 1997). The error in pressure drop prediction is claimed to be within ±11% for normal ranges of operation. It has a 'flow parameter' as the abscissa and a 'capacity parameter' as the ordinate.

Flow parameter, $F_{lv} = (L'/G')(\rho_G/\rho_L)^{0.5}$ (5.20)

Capacity parameter $= C_s F_p^{0.5} \nu^{0.05}$; $C_s = u_{sG}[\rho_G/(\rho_L - \rho_G)]^{1/2}$, in ft/s (5.21)

Interestingly, the abscissa and the ordinate of the Strigle's chart resemble the corresponding quantities of Fair's flooding chart for a tray tower [Figure 5.12(a)]. The flow parameter F_{lv}, represents the square root of the ratio of liquid and vapour kinetic energies. The ordinate describes a balance between forces due to vapour flow (that acts to entrain swarms of liquid droplets) and the gravity force that resists entrainment (Kister, 1992). Here F_p is a characteristic parameter of the packing, called the 'packing factor' (discussed in the next section). The quantity C_s, which is akin to the Souders–Brown constant [see Eq. (5.40], may be corrected for changes in interfacial tension and viscosity, if necessary.

$$(C_s)_{corr} = C_s(\sigma/20)^{0.16}(\mu/0.2)^{-0.11}; \quad [\sigma \text{ in dyne/cm}, \mu \text{ in cP}] \tag{5.22}$$

† The ordinate of Figure 5.34 has a linear scale and is more convenient to use than another version having a logarithmic ordinate (see Strigle, 1994).

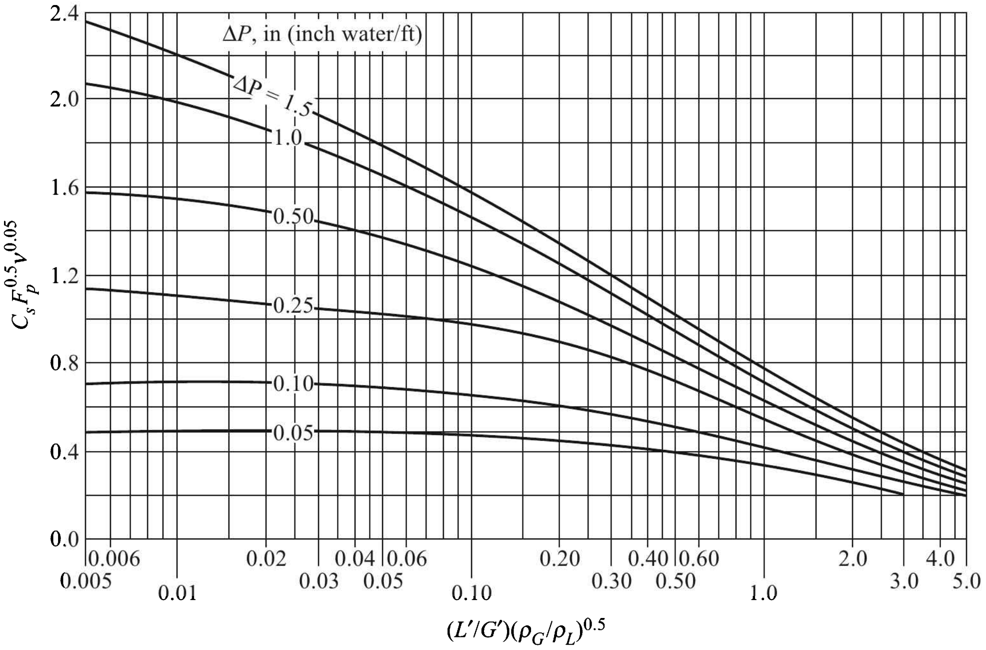


Figure 5.34 Strigle's GPDC (Strigle, 1994).

Strigle's chart also excluded the curve for pressure drop at flooding. However, the curve for $\Delta P/L = 1.5$ inches water per foot is considered to represent the 'incipient flooding' condition. Kister and Gill (1991) proposed the following correlation for flood point pressure drop in terms of the packing factor.

$$(\Delta P/L)_{fl} = 0.115F_p^{0.7} \quad \text{(inch water/ft; } F_p \text{ in ft}^{-1}) \tag{5.23}$$

Robbin (1991) proposed another set of correlations for pressure drop prediction over a wide range of operating conditions. For dry bed pressure drop at nearly atmospheric pressure, he suggested the following equation.

$$(\Delta P/L)_d = 2.78 \times 10^{-10} F_{pd}(G'^2/\rho_G) \quad \text{(inch water/ft)} \tag{5.24}$$

Here G' is in lb/ft^2·h, and ρ_G is in lb/ft^3. The above equation has an important application. The dry bed packing factor F_{pd} of any packing, which is now considered an empirical quantity (see below), can be calculated from the above equation by measuring the pressure drop across an experimental packed bed. However, the packing factors for dry and irrigated beds are likely to be different. The dry bed pressure drop can also be calculated using the Ergun's equation.

5.12.3 Packing Factor

The Eckert chart (and a few similar charts) contains a parameter F_p that characterizes the packing and is called 'packing factor' (an alternative notation C_f has also been used to denote this quantity). Originally introduced by Lobo in 1945, the packing factor used to be taken as a_p/ε^3 (a_p = surface area of the packing per unit volume†; ε = void fraction of the packed bed).

† This is *not* the same as the specific interfacial area of contact between the gas and the liquid.

This factor could be calculated from these two properties of a packing. It was later found that the pressure drop and flooding data could be better correlated if the packing factor was taken as an *empirical* quantity. In fact, it is now taken to be so and is determined by experimental measurement of pressure drop across a packed bed and using the generalized pressure drop correlation discussed below. The values of F_p for different packings are supplied by the manufacturers. The packing factor and a few other characteristics of several random packings are given in Table 5.9. The packing factor inversely indicates the capacity of a packing; the

Table 5.9 Characteristics of several tower packings

Random packings	*Size*	*Packing factor, F_p* (ft^{-1})	*Sp. surface area, a* (ft^2/ft^3)	*Voidage, ε*
Raschig ring (ceramic)	⅝ inch (15 mm)	380	100	0.69 2
	1 inch (25 mm)	179	56	0.68
	2 inch (50 mm)	65	28	0.74
Raschig ring (1/16-inch, metal)	25 mm	145	56.7	0.85
Berl saddle (ceramic)	½ inch (13 mm)	380	142	0.63
	1 inch	110	79	0.68
	1½ inch	65	46	0.71
Intalox saddle (ceramic)	1 inch	92	78	0.73
	1½ inch	52	59	0.76
	2 inch	40	35	0.76
Intalox saddle (plastic)	2 inch	28	37.2	0.91
Pall ring (metal)	1 inch	56	68.1	0.954
	2 inch	27	34.3	0.951
Pall ring (plastic)	1 inch	55	68.6	0.89
	2 inch	26	34	0.92
IMTP (metal)*	# 25	41	74.7	0.967
	# 50	18	24.7	0.978
CMR	1 inch	40	70.8	0.971
	1½ inch (38 mm)	29	53.3	0.974
Nutter ring (metal)*	# 1	27	51	0.978
	# 2	17	29	0.98
Bialecki ring	1 inch		72.5	0.94
	2 inch		37	0.966
Nor-Pac ring (plastic)	1 inch	31	55	0.927
	2 inch	14	26.4	0.947
Hi-flow ring (ceramic)	2 inch	29	27.3	0.81
Hi-flow ring (plastic)	2 inch	20	35.6	0.924
Hi-flow ring (metal)	2 inch	16	28	0.977
Structured Packings				
Gempak 2A (Glitsch)			68	0.95
3A			120	0.96
Flexipac 2 (Koch)			68	0.95
3			41	0.96
Mellapak 250Y (Sulzer)			76	0.988
350Y			107	0.975

* IMTP and Nutter rings are denoted by a number rather than a nominal size.

specific surface area indicates its mass transfer efficiency. It is intriguing that the values of the packing factor of the same packing obtained from different sources are found to vary.

5.12.4 Liquid Holdup

There must be a reasonable liquid holdup in the bed in order to facilitate mass transfer. However, excessive holdup increases pressure drop over the bed and is also undesirable if the liquid is heat-sensitive. Normally it ranges from a few percent to about 15% of the bed volume. Two types of liquid holdup (expressed as volume of liquid per unit bed volume) have been defined.

Static holdup: It is the amount of liquid remaining in unit volume of the bed after the bed is drained for a reasonable time. It is pretty small compared to the total holdup.

Operating holdup (h_{Lo}): It is the difference between the total holdup and the static holdup when the bed is in operation. It is also called 'dynamic holdup'. Several correlations for estimation of the quantity are available (Kister, 1992). A recent correlation (Engel et al., 1997) for h_{Lo} (volume fraction of the bed) given below is claimed to have an error within 16% for most systems.

$$h_{Lo} = 0.93\left(\frac{u_{Ls}^2 a_p}{g}\right)^{1/6}\left(\frac{\mu_L^2 a_p^3}{\rho_L^2 g}\right)^{1/10}\left(\frac{\sigma_L a_p^2}{\rho_L g}\right)^{1/8} \tag{5.25}$$

5.12.5 Minimum Wetting Rate (MWR)

It is the liquid throughput below which the film on the packing surface breaks up reducing the wetted area. A liquid rate below MWR is too small to wet all the packing surface. The effective interfacial area of the gas–liquid contact decreases and the efficiency of mass transfer decreases as a result. Among the many correlations available for its prediction, the one due to Schmidt (1979) has been found to work pretty well.

$$u_{sL} = 7.7\times 10^{-6}\left(\frac{\rho_L \sigma_L^3}{\mu_L^4 g}\right)^{2/9}\left(\frac{g}{a_p}\right)^{1/2} \text{ m}^3/\text{m}^2\cdot\text{h} \quad [g \text{ in m/s}^2;\ a_p \text{ in m}^{-1}] \tag{5.26}$$

Minimum liquid rate for random packings is reported to lie in the range 0.5–2 gpm/ft^2 (1.25–5 m^3/m$^2\cdot$h); for structured packing it is 0.1–0.2 gpm/ft^2 (0.12–0.25m^3/m$^2\cdot$h).

5.12.6 Determination of the Diameter of a Packed Tower and Packed Tower Design

The design of a packed tower for a particular service involves a number of things such as the selection of solvent, the selection of the type and size packing, the determination of column diameter and height of packing, and the design of column internals. Mass transfer phenomena in a packed tower and the determination of the height of packing for a given separation job will be taken up in Chapters 6 and 7. So far as column internals are concerned, there is no well-defined procedure. It may be done by using the limited information available in the open literature and the manufacturer's catalogue. In this section, we discuss one very important item of design, i.e. the determination of the diameter of a packed column.

There are broadly two approaches. One approach, based on the determination of the flooding† velocity by using the Eckert's GPDC chart (Figure 5.33), proceeds as follows. (i) From the total liquid and gas flow rates (either specified or calculated by material balance) the abscissa (i.e. the flow parameter, F_{lv}) is evaluated. (ii) The value of the ordinate is obtained from the flooding curve and the mass flow rate of the gas at flooding is calculated. (iii) The operating gas flow rate is *normally* taken as 70 to 80% of the flooding velocity to guard against inherent errors in the flooding curve and also to keep some flexibility in the design to take care of any sudden surge in the gas flow rate. Once the design gas flow rate is fixed, the tower diameter and the pressure drop across the bed may be estimated. The latter is obtained from the same chart, i.e. Figure 5.33. An algebraic correlation for the Eckert's flooding curve (and a dozen similar equations) has been given by Piche et al. (2001).

$$\log_{10}(Y)_{fl} = -0.296[\log(F_{lv})]^2 - 1.081\log(F_{lv}) - 1.668$$

$$(Y)_{fl} = \frac{(G')^2_{fl}\, F_p\,(\rho_w/\rho_L)(\mu_L)^{0.2}}{\rho_G\,\rho_L\,g_c} \tag{5.27}$$

[G' in lb/ft^2·h; F_p in ft^{-1}; ρ in lb/ft^3; μ in cP; g_c in ft.lb$_f$/lb$_m$·s^2]

The second approach does not use the flooding curve at all because of its limited accuracy and applicability. The allowable pressure drop in the bed is taken as a basis of design and the Strigle's GPDC chart is used directly. The value of the flow parameter is calculated and the capacity parameter corresponding to the allowable pressure drop is obtained from the chart. The column diameter is now easy to determine. The pressure drop at flooding for the particular packing can be calculated from the Kister and Gill equation [Eq. (5.23)]. The gas velocity at flooding can also be calculated from these results. A step-by-step procedure is outlined in Ludwig (1997). A few practical values of the allowable pressure drop, $\Delta P/L$ [(inch water)/(ft packing)], (Ludwig, 1997) are: low to medium pressure column operation: 0.4–0.6; absorption or similar systems: 0.25–0.4 for non-foaming systems, 0.1–0.25 for foaming systems;†† atmospheric pressure distillation: 0.5 to 1.0 inch; vacuum distillation: 0.1–0.2. The recommended sizes of packing for different column diameters are: D_c < 1ft, d_p < 1 inch; D_c = 1–3 ft, d_p = 1–1½ inches; D_c > 3 ft, d_p = 2–3 inches. Normally, d_p/D_c ranges between 1/20 and 1/10. Limited data and information on pressure drop calculation for a bed of structured packings are available (Fair and Bravo, 1990; Strigle, 1994; Olujic et al., 2001).

For the first generation random packings, the flood point pressure drop is about 2–2.5 inch water per foot of packed bed; for Paul rings, it is 1.5 inch per foot. For most modern packings, it is 0.5–1.5 inch per foot. Manufacturers of packings generally supply the pressure drop and flooding characteristics of their products as plots of ΔP versus F_s [= $u_{sG}(\rho_G)^{0.5}$]. It may be noted that the quantity F_s is also taken as a measure of the 'capacity parameter' or 'factor' for flow through a packed tower at low-to-moderate pressure when $\rho_G << \rho_L$. If enough data are available in the company's catalogue, it is desirable that the flooding point or pressure drop is determined by interpolation of the available data.

† Flooding limits the liquid and vapour flow capacity of a column. The assessment of the capacity of an existing column has been discussed by Capps (1993).

†† Anti-foaming agents are sometimes used to suppress foaming in an absorption column.

In order to maintain proper vapour distribution through the bed, the operating bed pressure drop should not be less than 0.1 inch water/ft. In a column operating near atmospheric pressure, the superficial gas velocity normally remains below 1 m/s; the liquid velocity remains around 1 cm/s. Common ranges of values of the more important packed-bed parameters are given in Table 5.10.

Table 5.10 Ranges of a few important packed-tower parameters

Random packing nominal size	$D_c/20$ to $D_c/10$, D_c = column diameter
Bed voidage	70 to 90% (more for structured packings)
Open area of packing support (for gas/liquid flow)	70 to 85% or more
Re-distribution of liquid	After 3 to 10 tower diameter (10 to 20 ft)
Gas pressure drop	Less than 0.5 inch water per foot bed depth
Operating velocity	70 to 80% of flooding velocity
Minimum wetting rate	0.5 to 2 gpm/ft^2 for random packings; 0.1 to 0.2 gpm/ft^2 for structured packings

EXAMPLE 5.2 A gas mixture containing 10% SO_2 and 90% inerts at 1 atm total pressure and 30°C is to be scrubbed with water to remove 97% of SO_2. The inerts have essentially the properties of air. The feed gas rate is 1500 kg/h and the water rate is 37,525 kg/h at the tower bottom. Estimate in each case the diameter of a packed tower for this service if either 1½ inch Raschig ring or 50 mm plastic Pall ring is used as the packing. Calculate the pressure drop across the tower for the second case and the blower horsepower required if the packed height is 5 m. The liquid properties are like those of water. Both gas and liquid flow rates are the maximum at the bottom and design calculations may be based on these values. The flow rates at the top can be easily calculated.

Solution

The tower diameter is to be calculated on the basis of the largest liquid and gas flow rates that occur at its bottom.

Given: Liquid rate, L = 37,525 kg/h; gas rate, G = 1500 kg/h at the bottom.

The pressure at the tower bottom will be above atmospheric. Since the pressure drop will not be large, we take the properties of air at 1 atm (1.013 bar) and 30°C (303 K).

Average molecular weight of the feed gas (90% air, 10% SO_2),

$$M = (0.9)(28.8) + (0.1)(64) = 32.3$$

$$\text{Gas density, } \rho_G = \frac{P}{RT}M = \frac{(1.013)(32.3)}{(0.08317)(303)} = 1.298 \text{ kg/m}^3 = 0.081 \text{ lb/ft}^3$$

Liquid viscosity (taken as that of water at 30°C),

$$\mu_L = 0.81 \text{ cP}; \qquad \text{surface tension} = 70 \text{ dyne/cm}$$

$$\text{density, } \rho_L \approx 996 \text{ kg/m}^3 = 62 \text{ lb/ft}^3$$

$$\text{Flow parameter, } F_{lv} = \frac{L'}{G'}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} = \frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} = \left(\frac{37{,}525}{1500}\right)\left(\frac{1.298}{996}\right)^{0.5} = 0.903$$

(a) *Calculation of column diameter—1½ inch Raschig ring packing* (d_p = 1½ inch): Use Eckert's GPDC chart (Figure 5.33) since it is good enough for a first generation packing. At flooding, for $F_{lv} = 0.903$, the capacity parameter is 0.021. The other parameters are:

$$\rho_w/\rho_L = 1; \qquad \mu_L = 0.81 \text{ cP}$$

Packing factor, $\quad F_p = 94.5/\text{ft}; \quad g_c = 4.18 \times 10^8 \text{ ft/h}^2$

i.e. $$\frac{(G')^2_{fl}\, F_p(\rho_w/\rho_L)(\mu_L)^{0.2}}{\rho_G\,\rho_L\, g_c} = 0.021 \quad \Rightarrow \quad (G')^2_{fl} = \frac{(0.021)(0.081)(62)(4.18\times 10^8)}{(94.5)(1)(0.81)^{0.2}}$$

$$\Rightarrow \qquad (G')_{fl} = 697.5 \text{ lb/ft}^2\text{h}$$

Take the operating gas flow rate as 70% of the flooding value.

$$\text{Operating } G' = (697.5)(0.7) = 488.3 \text{ lb/ft}^2\text{·h} = 2384 \text{ kg/m}^2\text{·h}$$

$$\text{Tower cross-section} = G/G' = 1500/2384 = 0.629 \text{ m}^2$$

$$\Rightarrow \qquad \text{Tower diameter, } D_c = \boxed{0.90 \text{ m}} = 2.94 \text{ ft} \approx 3 \text{ ft}$$

Now,

$$d_p/D_c = (1½ \text{ inch})/(36 \text{ inch}) = 1/24$$

This is acceptable. However, 2 inch rings could be used as well.
Let us calculate the *capacity parameter* at flooding for $F_{lv} = 0.901$ using Eq. (5.27).

$$\log_{10}(Y)_{fl} = -\,0.296[\log(0.903)]^2 - 1.081[\log(0.903)] - 1.668 = -1.665 \Rightarrow (Y)_{fl} = 0.0216$$

This appears to be close to the value (0.021) read directly from the chart.

(b) *Calculation of column diameter—50 mm Pall ring packing:* Use the Strigle version of the GPDC chart (Figure 5.34) since this is more appropriate for this packing.

Take the allowable pressure drop as 0.2 inch water per foot packing for this gas absorption operation.

For $F_{lv} = 0.903$ (calculated before) and $\Delta P/L = 0.2$ inch water/ft, the capacity parameter = 0.52 is obtained by interpolation from the chart. Take $F_p = 25 \text{ ft}^{-1}$; $\nu = 0.81$ centistoke.

$$\Rightarrow \qquad C_s(F_p)^{0.5}\nu^{0.05} = 0.52 \quad \Rightarrow \quad C_s(25)^{0.5}(0.81)^{0.05} = 0.52$$

$$\Rightarrow \qquad C_s = u_{sG}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{0.5} = 0.105$$

$$\Rightarrow \qquad u_{sG} = (0.105)\left(\frac{996 - 1.298}{1.298}\right)^{0.5} = 2.91 \text{ ft/s}$$

$$= 0.886 \text{ m/s} = \text{superficial gas velocity}$$

$$\text{Volumetric gas flow rate} = \frac{1500 \text{ kg/h}}{(1.298 \text{ kg/m}^3)(3600 \text{ s/h})} = 0.321 \text{ m}^3\text{/s}$$

$$\text{Tower cross-section} = (0.321 \text{ m}^3\text{/s})/0.886 \text{ m/s} = 0.362 \text{ m}^2$$

$$\Rightarrow \qquad \text{Tower diameter, } D_c = [(0.362)(4)/\pi]^{1/2} = \boxed{0.68 \text{ m}}$$

[Compare this with D_c = 0.9 m in case (a)]

Thus, a substantially smaller diameter column is sufficient if the *second generation packing* is used.

Pressure drop at flooding for the Pall ring-packed column,

$$\begin{aligned}(\Delta P/L)_{fl} &= 0.115(F_p)^{0.7} \\ &= (0.115)(25)^{0.7} \\ &= \boxed{1.09 \text{ inch water per foot packed height}}\end{aligned}$$

Blower power requirement for feeding the gas: The tower is designed for $\Delta P/L = 0.2$ inch water per foot of packing.

Pressure drop across the bed of 5 m height, $\Delta P = (0.2)(5/0.3048) = 3.28$ inch water.

Add 10% to take into account contraction, expansion and other losses (nozzles, packing support, etc.)

$$\begin{aligned}\text{Operating pressure drop} &= (3.28)(1.1) = 3.61 \text{ inch water} = (3.61)(0.0254)(996)(9.81) \\ &= 895 \text{ N/m}^2 \\ \text{Gas flow rate, } G &= 1500 \text{ kg/h} = 0.4167 \text{ kg/s} \\ \text{Power requirement} &= \left(\frac{\Delta P}{\rho}\right)G = \left(\frac{895 \text{ N/m}^2}{1.298 \text{ kg/m}^3}\right)(0.4167 \text{ kg/s}) \\ &= 287.5 \text{ N·m/s} = 287.5 \text{ W}\end{aligned}$$

Take 65% overall efficiency of the motor-blower assembly.

$$\text{Actual power requirement} = 287.5/0.65 = 442 \text{ W} = \boxed{0.6 \text{ hp}}$$

A motor of this rating is not available, and a ¾ hp motor is uncommon. A blower of suitable design and powered by a 1 hp motor is recommended.

Calculation of operating liquid holdup: It is rather simple to calculate h_{Lo}, the operating liquid holdup, using Engel's equation, Eq. (5.25). The values of the different quantities are: for 2 inch Pall ring, $a_p = 102$ m^2/m^3; $\mu_L = 0.81$ cP $= 8.1 \times 10^{-4}$ kg/m.s; $\sigma_L = 70$ dyne/cm $= 0.07$ N/m; superficial liquid velocity, $u_{sL} = [(37{,}525/996)$ m^3/h$]/(0.362$ m$^2) = 0.0289$ m/s.

Putting the values in Eq. (5.25), the volume fraction liquid holdup in the bed

$$\begin{aligned}h_{Lo} &= (0.93)\left[\frac{(0.0289)^2(102)}{9.81}\right]^{1/6}\left[\frac{(8.1\times10^{-4})^2(102)^3}{(996)^2(9.81)}\right]^{1/10}\left[\frac{(0.07)(102)^2}{(996)(9.81)}\right]^{1/8} \\ &= 0.0588 \text{ m}^3 \text{ liquid per m}^3 \text{ bed volume}\end{aligned}$$

A typical packed bed data-sheet incorporating the basic design information and parameters is given in Table 5.11. Since complete design of the bed has not been done here, only the approximate values of a few of the parameters have been given in the data sheet. The objective of inclusion of the data sheet is just to give an idea about what a design data sheet is.

Table 5.11 Packed bed data sheet

Service: ABSORBER		*Item Number: B-27-0103*	
Packed Bed Data			
	Top		*Bottom*
Vessel ID, mm		680	
Bed depth, mm		5000	
Random packing, mm		5000	
Packing type		50 mm Pall ring	
Fluid description		Water	
Hold down plate		KG- TP825	
Packing support plate		KG- TP814	
Liquid distributor		KG- TP916	
Structural design temperature, °C		150	
Liquid flow rate, kg/h	37,335		37,525
Density, kg/m^3	995		996
Viscosity, cP		0.81 (average)	
Surface tension, dyne/cm		70 (average)	
Temperature, °C		30 (average)	
Pressure, kPa	101.3		102.1
Gas flow rate, kg/h	1210		1500
Density	1.16		1.298
Foam deaerating factor			0.75
Demister		Yes	

Note 1: The liquid distributor is to be placed 200 mm above the packing hold down plate.
Note 2: 'KG' refers to a Koch-Glitsch product of the given product number.

5.13 THEORETICAL MODELS OF FLOW THROUGH A PACKED TOWER

There have been a number of attempts to develop simplified models of two-phase (the gas and the liquid) flow through a packed bed for a better understanding of the flow phenomena as well as to theoretically determine the pressure drop and the flooding capacity. Any such model visualizes a simplified picture of the bed and of flow through it so as to make it amenable to theoretical analysis. Three models are cited here.

The particle model: In this model, the packed bed is visualized as consisting of a number of spheres of a size calculated on the basis of the void volume of the bed and the surface area of the packing (Figure 5.35). If the voidage is large (say over 0.4), the hypothetical spheres may not even touch each other (as if they remain 'suspended' but stationary). Pressure drop across the bed is a result of drag of the flowing gas on the spheres. With increasing liquid flow, the void volume in the bed decreases, the size of the hypothetical spheres increases and the pressure drop also increases. In fact, an early version of the model was used by Ergan back in 1952 to develop

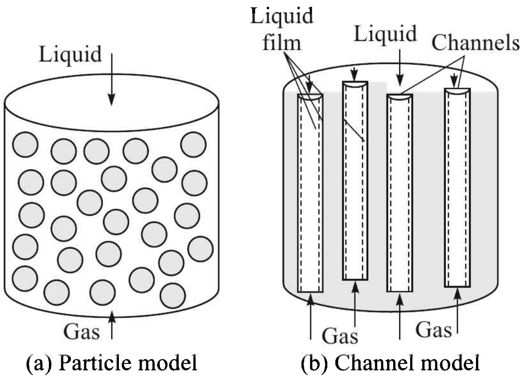


Figure 5.35 Models of a packed bed.

an equation for pressure drop across a packed bed of solid. Stichlmair et al. (1989) used this model to predict pressure drop and flooding for both random and structured packings.

The channel model: In this model, the packed bed is considered to act like a cylindrical block with a number of uniformly distributed vertical channels in it. The hypothetical channel diameter can be calculated from the voidage and specific area of the packings. The liquid flows as a film along the walls of the cylinders and is subject to shear force at the gas–liquid interface because of the upflowing gas. Billet (1995) used this model to develop equations for gas-phase pressure drop and the condition of beginning of loading of liquid in the bed. Loading starts when the shear force at the interface is large enough to reduce the liquid and vapour velocities at the interface to zero. The flooding conditions were also analytically laid down as

$$\frac{du_L}{dh_L} = 0 \quad \text{and} \quad \frac{du_G}{dh_L} = 0 \quad \text{for } u_L = u_{L,fl} \text{ and } u_G = u_{G,fl} \tag{5.28}$$

Here u_L is the superficial liquid velocity and h_L is the liquid holdup in the bed. Billet (1995) and the German group used these criterion to determine the flooding capacity of the bed. The model has been criticized by some people because it visualizes the packing material to form a continuous medium. Nevertheless, it has been used by other people too (e.g. Rocha et al., 1993) to predict packed bed pressure drop.

Percolation model: This model (Hanley, 1994) assumes that a part of the liquid flowing through the bed gets accumulated in certain locations of the bed causing local blockage or 'localized flooding'. This creates the enhanced pressure drop. The number of flooded locations increases with the increasing liquid rate.

5.14 COMPARISON BETWEEN PACKED AND PLATE TOWERS

Tray columns and packed columns are the two most widely used devices for distillation, gas absorption and stripping, and, to some extent, for liquid–liquid extraction. Each class has characteristic but very different 'column internals' for achieving intimate contact between the two phases. But the mechanism by which gas–liquid contacting occurs in a tray column is totally different from that in a packed column. This gives rise to differences in the operating features as well as applications of these devices (Chen, 1984). Relative advantages and limitations of tray and packed columns have been dealt with by many researchers and neatly summarized by Kister (1992). Capacity and efficiency comparison of sieve trays, valve trays, and random and structured packings has been done by Kister et al. (1994).

(i) *Pressure drop:* The open area for gas (or vapour) flow in a tray tower typically varies from 6 to 15% of tower cross-section, whereas that for a packed tower is often greater than 50% of the tower cross-section. For a packed tower with structured packings, it is more than 90%. So the pressure drop per theoretical stage is much less in a packed tower than in a tray tower. It is about 3–5 mm Hg per stage in a tray tower which is more than three times the pressure drop per HETP for a tower filled with random packings and more than ten times for that having structured packings. The gas compression energy required for a packed tower is significantly lower than that in a tray tower. This advantage becomes particularly important in vacuum applications where packed towers, particularly with structured packings, are the choice.

(ii) *Liquid holdup:* For a tray tower, the liquid holdup remains within 8 to 12% of tower volume against 1 to 6% in case of a packed tower. So the packed tower offers a smaller liquid residence time and is more suitable for processing heat sensitive liquids.

(iii) *Corrosion:* Ceramic and plastic packing materials are highly corrosion resistant. Even the shell of a packed tower may be made of a few smaller pieces of ceramic shell with bell and spigot joints[†] as stated before. The tray towers, on the other hand, are made of metals or alloys and possess more internals. So, a packed tower is the choice for a highly corrosive service. For example, a packed tower is used for absorption of SO_3 in a sulphuric acid plant, for nitric acid concentration by extractive distillation, and for drying of moist chlorine gas in a caustic-chlorine plant.

(iv) *Foaming liquids:* It is difficult to process a foaming liquid in a tray tower since bubbling aggravates the problem of foaming and flooding. The problem is less severe in a packed tower.

(v) *Suspended solids:* The packings are more prone to deposition and choking if the liquid has suspended solids in it. A tray tower can handle a dirty liquid or a slurry with relative ease. Also, it can be cleaned easily. Cleaning of packings, particularly the structured ones, is difficult.

(vi) *Heat removal:* If there is an excessive heat generation (this may occur in case of 'reactive distillation' or for absorption with reaction) necessitating intermediate cooling of the liquid, a tray tower is convenient. A tray can be provided with a cooling coil without much difficulty. Alternatively, the liquid from a tray may be withdrawn, passed through an external cooler and fed to the next tray. However, liquid cooling cannot be done easily and efficiently in a packed tower.

There are a few other factors that affect selection between these two towers. A packed tower can be operated at a low gas rate, but a tray tower is prone to weeping and liquid dumping if the gas flow rate is insufficient. On the other hand, a tray tower with suitable tray design can handle a large liquid rate that a packed tower may not because of possible flooding. A tray tower

[†] This kind of joint is frequently used to join cast iron pipes.

can be made to function at a low liquid rate by using a reverse flow tray; a packed tower may not wet properly if the liquid rate is low. The liquid distributors of a packed tower may get clogged at a low liquid turndown. Also there is a greater uncertainty in predicting the performance of a packed tower. The hydrodynamics of two-phase flow in a packed bed is less well-understood. A tray tower can be equipped with multiple nozzles for intermediate feed supply or product withdrawal, but it is difficult to do it in a packed tower because a liquid collection and redistribution device has to be installed within the tower for each such nozzle. However, a packed tower is cheaper. A tray tower has many more internal components (a number of trays, supports, downcomers, weirs, etc.) than those a packed tower (a packing support and one liquid redistributor for about 15 ft of packing). Thus the former entails substantially more fabrication cost. A tray tower smaller than 3 ft in diameter becomes much more expensive to build (since a tray cartridge has to be used), and hence is not preferred.

NOTATIONS

$\bar{a}$: specific interfacial area of gas–liquid contact; ft^2/ft^3, m^2/m^3

a_p : specific surface area of the packing; ft^2/ft^3, m^2/m^3

A_a : active tray area (= cross-section – downcomer area); ft^2, m^2

A_d : downcomer area (one side only); ft^2, m^2

A_{da} : area for liquid flow below the downcomer apron; ft^2, m^2

A_h : total area of the holes on a sieve tray; ft^2, m^2

A_T : tray or column cross-section; ft^2, m^2

C_o : orifice discharge coefficient

C_s : the quantity defined in Eq. (5.21)

C_{SB} : Souders–Brown flooding constant, ft/s

d_H : sieve tray hole diameter; inch, mm or m

d_p : 'nominal size' of a packing; inch, mm

f_a : fractional hole area, A_a/A_T

f_d : fractional downcomer area = $1 - 2A_d/A_T$

f_h : fractional hole area, A_h/A_a

F_{lv} : packed or tray tower flow parameter

F_p : packing shape factor, a_p/ε^3; ft^{-1}, m^{-1}

h_{ad} : head loss for liquid flow below the downcomer apron, inch liquid

h_c : 'clear liquid height' on a tray, inch

h_d : dry tray pressure drop, inch liquid

h_{db} : downcomer backup, inch liquid

h_l : pressure drop for flow of the gas through the aerated liquid, inch liquid

h_{ow} : height of liquid over the weir (in terms of clear liquid), inch
h_t : total tray pressure drop, inch liquid
h_w : weir height, inch
h_σ : liquid head corresponding to surface tension force, Eq (5.19), inch liquid
G, L : gas or liquid flow rate; lb/h, kg/s
G', L' : gas or liquid mass flow rate; lb/ft^2·h, kg/m^2·s
Q_L : liquid flow rate over the weir, gpm per inch weir length
S : tray spacing; inch, m
u_h : gas velocity through the holes; ft/s, m/s
u_s : superficial fluid velocity (based on active tray area for a tray column, cross-section for a packed column (subscript L = liquid, G = gas or vapour); ft/s; m/s
$u_{s,fl}$: superficial flooding velocity of the gas; ft/s, m/s
$(Y)_{fl}$: ordinate of the GPDC flooding curve, Eq. (5.27)
β : aeration factor, Eq. (5.16)
Δ : hydraulic gradient, inch or mm liquid
μ_L : liquid viscosity; cP or kg/m.s
φ_d : relative dispersion density
ρ : density; lb/ft^3, kg/m^3 (subscript L = liquid, G = gas)
σ_L : surface tension; dyne/cm, N/m

MULTIPLE CHOICE QUESTIONS

1. Gas–liquid contacting may be broadly classified into the following three categories:
(i) gas dispersed in the liquid
(ii) liquid dispersed in the gas
(iii) both the gas and the liquid are continuous.

Indicate the category to which each of the following devices belongs by putting the appropriate serial number within the brackets:
Packed tower ( ); Tray tower ( ); Spray tower ( ); Falling film absorber ( ); Bubble column ( ); Agitated vessel ( ).

2. Specific interfacial area in a packed column is defined as
(i) the effective area of contact between the gas and the liquid per unit bed volume
(ii) the actual surface area of the packing per unit volume
(iii) the total wetted area of the packing in the bed.

3. The grid packing is suitable for gas absorption if
(i) a large liquid rate has to be handled

(ii) the feed gas has a high solute content
(iii) a large gas rate is to be handled at a low pressure drop.

4. Saddle packings offer less pressure drop than Raschig rings because of their
(i) larger fractional voidage
(ii) smooth surface finishing
(iii) aerodynamic shape.

5. Which of the following three types of packing is most efficient?
(i) Intalox saddle
(ii) Berl saddle
(iii) Cross partition ring

6. Which of the following three packings offers the lowest pressure drop?
(i) Plastic Raschig ring
(ii) Metal Paul ring
(iii) Ceramic Intalox saddle

7. Dynamic liquid holdup in a packed tower is defined as
(i) the volume of the packed section less the true volume of the packing
(ii) the amount of liquid sticking to the packing and held up in the interstices after the tower operation is stopped
(iii) the amount of liquid contained in the bed when the tower is in operation.

8. Which of the following sizes of saddles would you recommend for filling a column of 1.5 m diameter?
(i) ½ inch (ii) 1 inch (iii) 3 inch

9. The open area of the packing support should be
(i) more than 70%
(ii) not more than 50%
(iii) at least 90%.

10. Which of the following techniques is effective for reducing entrainment of liquid droplets in the gas leaving a packed bed?
(i) Placing the liquid distribution points a little below the top of the packing
(ii) By using large size packings
(iii) By putting a layer of stacked cross partition rings above the randomly packed bed

11. What is the range of void volume of most structured packings?
(i) 50–80% (ii) 70–80% (iii) 90–98%

12. A 3 ft diameter column should have a packed height of 40 ft. How many liquid redistributors would you recommend?
(i) None (ii) 2 (iii) 6

13. Which of the following is an acceptable tray spacing in a 2 m column operating at 10 kg/cm^2 pressure?
(i) 15 cm (ii) 0.7 m (iii) 1 m