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Pour Point Density Estimations for Packed Columns with Structured Packings

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In the chemical processing industry (CPI), structured packings are widely used for distillation and absorption columns. To achieve the desired mass transfer performances of structured packings, it is crucial to distribute the liquid uniformly across the top of the packed bed. It is equally important to have an adequate number of pour points across the entire column cross section. A study on the pour point density required for liquid distributors employed in a packed column was conducted. This paper presents a simple method of estimating the required pour point densities for a packed bed with the structured packings. The effects of structured packing geometric parameters and process conditions on the requisite pour point densities are discussed in this paper. The method provides insights of the effect of packing geometries on the pour point density and can be used as the guidelines of liquid distributor preliminary designs.

1. Introduction

Packed columns are employed extensively in distillation and absorption applications due to their high capacities, low pressure drops and good mass transfer efficiencies. Good liquid and vapour distributions are critical to the attainment of expected separation efficiencies. A liquid distributor must be designed to distribute the liquid uniformly across the entire column cross section for all anticipated flow rates. Another key design criterion of a good liquid distributor is a sufficient number of pour points for the wetting of the packing surface. It is also important to have an adequate open area for vapour flow through the distributor so that the column hydraulic capacity will not be restricted by the liquid distributor.

Out of the four key design criteria of the liquid distributor designs, the effect of the liquid and vapour maldistributions on the packed column performances has been extensively studied. Severe liquid maldistribution results in some of the packing surface not being wetted, which reduces the interfacial mass transfer area. Any maldistributions also affect mass transfer driving forces. Local deviations from intended vapour to liquid ratios result in more or less material being transferred at such points than what was desired, and may even result in a local pinch condition. Liquid maldistribution studies on random packing and structured packing were conducted by many researchers (Hoek et al., 1986, Kunesh et al., 1987, Fitz et al., 1999, Cai et al., 2003, Rukovena et al. 2008). Several vapour maldistribution studies have also been reported (Porter et al., 1993; Muir and Briens, 1986, Cai et al., 2003). The first two vapour maldistribution studies emphasized the hydraulic performances of vapour distributors. The study by Cai et al. focused on the effect of vapour maldistributions on the mass transfer performances.

In addition to experimental studies on liquid and vapour maldistributions, several theoretical studies have been conducted to quantify the effects of liquid maldistributions on the packing mass transfer performances. One of the earliest works was done by Yuan and Spiegel (1982), who investigated the sensitivity of the packed column performance to liquid maldistribution using a two column model. Moore and Rukovena (1986) looked at acceptable distributor quality vs the number of theoretical stages. Billingham and Lockett (2001) subsequently used a parallel column model to identify the sensitivity of a separation to small maldistributions as a function of both relative volatility and the required number of stages.

Out of the four key distributor design criteria (uniformity of flow, pour point density, irrigation at column wall, and open area for vapour flow), very few experimental and/or theoretical studies have been done on the effect of pour point density on structured packing performances. Olujic et al. (2009) illustrated experimentally the effect of pour point density on liquid distribution performance with three different sizes of structured packings. Some of the vendors (Koch-Glitsch, 2018) may recommend the pour point densities required for their proprietary structured packings, however, there is no tool in the literature that can be used to estimate the pour point density required in a packed column with the structured packing. To fill that gap, this paper presents a simple method for estimating the minimum pour point density required for a packed column with structured packings, and provides insights regarding the effect of packing geometries on pour point density requirements. A new tool for the preliminary liquid distributor designs is presented.

2. Structured packing geometries

There are three major types of structured packings employed in industries, and each type has its preferred area of application. Gauze structured packing is made of fabrics woven from fine diameter wire of various materials. It is usually used for difficult separations such as isomers, fine chemicals, flavors, and perfumes. Gauze packings should be avoided in solid-containing and fouling services. Grid structured packings have high void fractions but small packing specific areas, but they feature high capacities and high resistances to plugging and fouling. Conversely, they have very low mass-transfer efficiencies. They are primarily used in direct-heat transfer, scrubbing, and de-entraining applications and for solid-containing and fouling services. Corrugated sheet metal structured packings are by far the most often used structured packings and are suitable for many services (except for some high liquid rate and/or high pressure distillation systems).

Corrugated sheet metal structured packings consist of corrugated steel metal sheets placed side by side, with opposing inclination angles of the ridges; the surfaces of the sheet metals are commonly perforated and textured. The perforations of sheets are intended to promote liquid and vapour radial mixing, and improve liquid distribution. Figure 1 is a photo of an actual structured packing sheet with a nominal surface area of 250 m^2/m^3. As shown in the photo, the liquid flows downward along the corrugation channels with a small fraction flowing through the perforations on the packing sheets.

Figure 1: Photo of a typical structured packing sheet

Compared to random packings, structured packings are highly organized in nature. There are some rather simple geometric relationships. Figure 2 is a simplified two dimensional representations of a corrugation, showing main geometrical parameters.

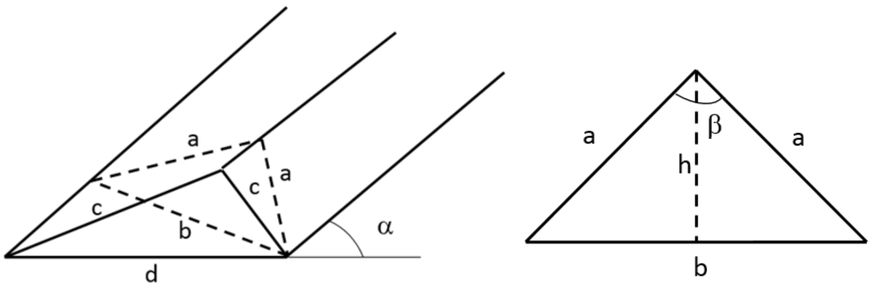

Figure 2: Structured packing corrugation geometries

As shown in Figure 2, the isosceles triangle is a plane normal to the flow channels, i.e., perpendicular to the corrugations. The packing geometric parameters and units are presented as follows:
where:

b is the channel width perpendicular to the corrugation, m
d is the horizontal distance between two ridges, m;
h is the crimp height, m;
H is the packing layer height, m;
α is the crimp inclination angle measured from the horizontal;
β is the crimp angle.

Regarding crimp inclination angle α, an angle of 45 degree is usually called "Y" Type; 60 degree "X" Type; 30 degree "Z" Type.

3. Model Development

3.1 Liquid flow inside packing sheet

The objective of this work was to develop a simple method for the estimation of the number of pour points required for a specific structured packing. The method is intended to provide a guideline for initial liquid distributor designs. Figure 3 is the top view of a block of structured packing that would install in a vertical cylindrical column wall.

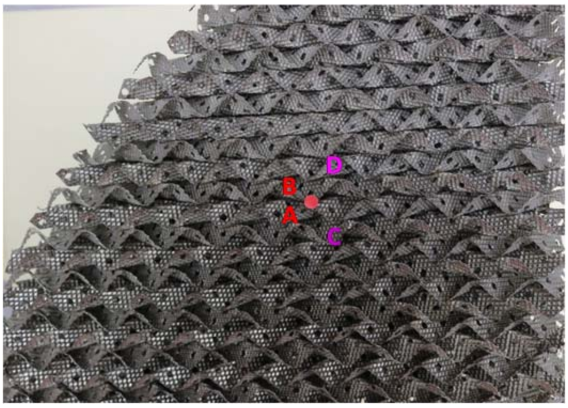

Figure 3: Top view of structured packing with pour point and neighbouring sheets

As shown in Figure 3, when the liquid stream exiting a distributor pour point hits the contact point of two ridges, as marked in the red solid circle, the liquid from this point will flow and irrigate the four sheets around it, specifically, the sheets marked with symbols A and B, and also the two adjacent sheets marked with symbols C and D. This irrigation, i.e., wetting, of four sheets by one pour point was validated by simple water experiments.

Since each sheet is perforated, some of the liquid flowing down every sheet will flow downwards to the other channels in the same sheet as indicated in Figure 4. For one sheet metal of the structured packing, the total volume with the packing surfaces wetted from one pour point consists of two parts, a rectangular cuboid and a triangular prism.

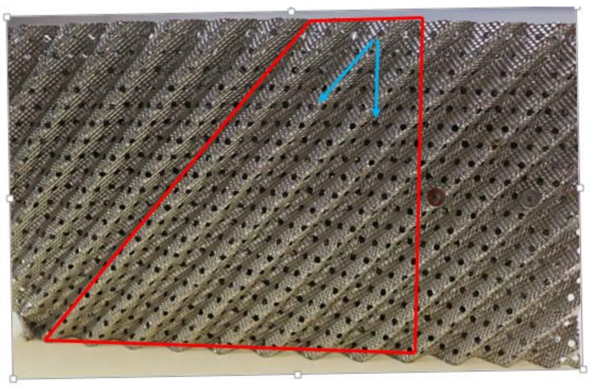

Figure 4: Surface area wetted by a single pour point

3.2 Method for estimating the required pour point density

A well-designed liquid distributor must provide an adequate number of pour points to have uniformly distributed liquid on the top surface of all the top packing blocks. As discussed above, the liquid from a single pour point will be separated or spread onto four neighboring sheets. For each sheet, the liquid will flow not only within two corrugated channels but also downwards into the channels below. The total volume of the packing with all the surfaces wetted by the liquid flow from a single pour point is shown in Figure 5.

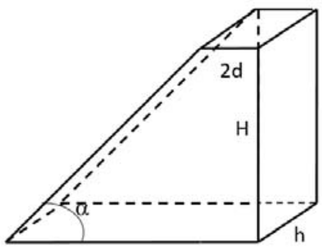

Figure 5: Packing volume of one sheet of packing with surface areas wetted from one pour point

As shown in Figure 5, for a single sheet of structured packing, the volume of the packing that all the surfaces are wetted by one pour point can be divided into two parts. One part is the tall rectangular cuboid and the other part is the triangular prism. The total volume of those two parts can be calculated using the following equation:

$$V_1 = \left(2 \cdot d \cdot H + \frac{H^2}{2 \cdot \tan\alpha}\right) h \qquad (1)$$

Since the liquid from one pour point is spread onto four sheets around it, as shown in Figure 3, the total packing volume with the wetted surface areas for all four sheets of packing is expressed as follows:

$$\mathrm{V} = \left(8 \cdot d \cdot H + 2 \cdot \frac{H^2}{\tan\alpha}\right) h \qquad (2)$$

Multiple pour points are required to wet the entire layer of structured packings. The number of pour points, N, required to irrigate the entire top layer can be easily derived from Eq(2)

$$\mathrm{N} = \frac{\pi D^2}{4 \cdot \left(8 \cdot d + 2 \cdot \frac{\mathrm{H}}{\tan\alpha}\right) h} \qquad (3)$$

where D is the column diameter, m.

It can be seen from the Eq(3), that the total number of the pour points is proportional to column cross sectional area, and is related to various packing geometrical parameters. In general, the pour point density is used for liquid distributor designs. The pour point density is defined as the number of pour points per unit cross-sectional area of the packed column. From Eq(3), a simple formula for estimating the pour point density can be stated as follows:

$$\mathrm{PPD} = \frac{1}{\left(8 \cdot d + 2 \cdot \frac{H}{\tan\alpha}\right) h} \qquad (4)$$

The pour point density estimated from Eq(4) assumed that there was no rotation between packing layers. However, for structured packing installations, it is the general good industrial practice to rotate each successive layer of packing 90 degrees from the previous layers to promote and improve liquid redistribution. The 90 degree rotation of the packing layers eventually and essentially doubles the total volume of the packing with the surface area wetted by a single pour point. Therefore, with the 90 degree rotations between packing layers, the minimum pour point density required for a liquid distributor for a specific structured packing is as follows:

$$\mathrm{PPD}_r = \frac{1}{\left(16 \cdot d + 4 \cdot \frac{H}{\tan\alpha}\right) h} \qquad (5)$$

This simple formula can be used for preliminary liquid distributor designs, for existing liquid distributor ratings, and for packed column troubleshootings.

4. Results and discussion

A simple method of estimating the pour point density for a liquid distributor was developed as shown in Eq.(5). The required pour point density depends on packing geometries, such as the crimp height, the crimp inclination angle, the channel width, and the layer height. Based on this simple method, for sheet metal structured packings with a nominal inclination angle of 45 degrees, the following table shows the effect of packing specific surface area on the calculated pour point density.

Table 1: Structured packing pour point densities with different specific surface areas

Packing size*	Specific surface area, m^2/m^3	Pour point density, points/m^2
250Y	250	60
350Y	350	102
500Y	500	160

*The crimp angle for these packings is assumed to be 90 degrees

As expected, more pour points are required for a higher specific surface area packing. When the packing specific area is doubled from 250 m^2/m^3 to 500 m^2/m^3, the pour point density required for the liquid distributor needs to be increased by a factor of almost three.
Contrary to general guidelines of liquid distributor designs, according to Eq(5), the pour point density of a liquid distributor depends on the crimp inclination angle measured from the horizontal. A larger crimp inclination angle requires a higher pour point density. For structured packings with the same specific surface area of 250 m^2/m^3, the X type packing with a crimp inclination angle of 60 degrees needs to have a higher pour point density as shown in the Table 2 below.

Table 2: Distributor pour point density with different inclination angles

Packing size*	Specific surface area, m^2/m^3	Pour point density, points/m^2
250Y	250	60
250X	250	89

*The crimp angle for these packings is assumed to be 90 degrees

It is generally held that the X type structured packings have the lower separation efficiencies and higher capacities than Y type packings do when the same liquid distributor is used. The present study indicates, for the structured packings with the same surface areas, that the X type packing requires higher pour point densities than the Y type packing does. It will be interested in collecting mass transfer data for the same surface areas of the X and Y types structured packings using the distributors with different pour point densities.

4.1 The effect of liquid distribution quality and pour point layout

The required pour point densities estimated above were based on the assumptions that the liquid is distributed in discrete streams and that all the pour points have the same liquid flow rate, in other words, the liquid distribution is perfectly uniform. In reality, this is not generally true as the liquid distribution could never be "perfect" across the entire top surface of a packing bed. The uniformity of liquid flow distribution is generally measured by the standard deviation of the liquid flows through the pour points. Generally, the standard deviation of the liquid flow rates is usually limited to between 5% (for mass transfer or heat transfer with a close temperature approach) and 10% (for general heat transfer) of the mean flow rate for all anticipated flow rates. Considering the "never perfect" initial liquid distribution from any liquid distributor, the pour point density suggested in the proposed method may be considered as the minimum density required.The precise layout of the distributor pour points will, of course, affect the liquid distribution uniformity and quality. It is important to have the pour points uniformly distributed across the top surface of the structured packing.This is not easy to implement in actual distributor designs, particularly for trough-type liquid distributors. Fortunately, liquid irrigation along the column wall for structured packings is not as important as that for random packings as the structured packing crimp inclination angles help direct a portion of the liquid towards to the column wall.

4.2 Deep vacuum applications

For deep vacuum distillation applications, the liquid rate is usually very low. For those applications, the gauze type structured packings are commonly used. Since such packings have a design similar to corrugated sheet metal structured packings, Eq(5) can also be applied to liquid distributor designs for gauze packings. However, when the liquid flux is below 5.0 $m^3/h\text{-}m^2$, the liquid may not have sufficient momentum or capability to spread across and penetrate the surface of the structured packing. In this case, additional pour points will likely be needed for the gauze type of structured packings.

4.3 High capacity structured packings

Since the late 1990's, more and more high-capacity structured packings have been used in distillation and absorption columns. These high-capacity structured packings provide smooth transitions for the liquid and vapour streams as they flow vertically from layer to layer. Compared to conventional structured packings, these smooth transitions reduce the liquid holdup at the interface of adjacent layers so the onset of the liquid entrainment is delayed. These high-capacity packings offer higher flood capacity than the conventional structured packings, and have similar or better mass transfer efficiencies. The method proposed in this paper can also be directly applied to the liquid distributor design for high-capacity structured packings.

5. Conclusions

The pour point density of a liquid distributor is one of the most important design criteria for a packed column. A simple method for estimating the pour point density for a given sheet metal structured packing is proposed in this paper. The method indicates that the required pour point density strongly depends on structured packing geometries, such as crimp heights, crimp inclination angles etc. Since the method was developed based on a perfectly uniform liquid distribution, the actual pour point density required may need to be higher for real situations. For heat transfer applications, the HETPs are generally very high; the pour point densities can actually be lower than those estimated by this new method. The proposed method can be applied to both conventional and high-capacity structured packings. However, for gauze type structured packings, the pour point densities estimated by this method may be too low, and additional pour points will be needed.

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