A NEW PRESSURE DROP MODEL FOR STRUCTURED PACKING

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ABSTRACT

A new pressure drop model for Mellapak™ 750YL, 500YL and 350YW structured packing has been developed. The model is general and uses only geometry parameters. It has a theoretical basis and is very different from other pressure drop models, particularly in the regime where liquid is loading on the packing. In this paper the model is described, and its predictions are compared with experimental observations of pressure drop from the Separations Research Program (SRP), Fractionation Research Inc. (FRI) and the University of Nottingham, UK. It has been found to provide good predictions of pressure drop. Models for predicting the packing capacity and liquid hold-up have also been developed.

Introduction.

In recent years there has been a rapid move towards using structured packing in commercial distillation columns. The advantages over tray columns include lower pressure drop, greater efficiency and ease of installation.

The prediction of pressure drop and operating loading are very important in column design. Various prediction methods are available, including the Bravo-Rocha-Fair (1992) and the Stichlmair-Rocha-Fair(1989) models. The homogeneous nature of structured packing lends itself much more to analytical models of behaviour than was possible for random packing. The background to this has been covered comprehensively recently (Stichlmair & Fair, 1998).

The new model developed and outlined in this paper is based on fundamental principles, and attempts to account for the real packing geometry that affects the pressure drop and flooding characteristics. To avoid confusion with regard to the various definitions of the flood point, we refer to the point where the mass transfer efficiency decreases as the *efficiency flood point* (if there is a sharp deterioration), the point where the pressure drop equals 12 mbar/m as the *pressure drop flood point*, and the point where the liquid splashes above the packing, observed visually, as the *visual flood point*. This is illustrated in Figure 1. The *visual flood point* can occur before or after the pressure drop flood point, as the latter is set at 12 mbar/m, and is not related to the packing or physics.

Model Background

From inspection of the experimental data it was postulated that there are two separate contributions to the pressure drop. The first part of the model predicts the pressure drop in the pre-loading regime, where the effect is caused by friction as the vapour flows through the packing. The second contribution to the pressure drop is added when the liquid starts to load onto the packing. It can be seen from Figure 1 that the pressure drop increases more rapidly in this region.

1. *Pre-loading regime*.

The counter-current liquid flows down over the packing in a thin film. It is assumed that the liquid wets the surface of the packing completely within a short distance from the distributor at the top of the bed. The success of using the relative velocity between the vapour and liquid phases for modelling mass transfer (Bravo et al., 1985) suggested its use for modelling the pressure drop. This resulted in a simple model for pressure drop below the loading point, where a constant friction factor gives an accurate fit. The pressure drop also scales correctly with the packing area (or channel side dimension). Other pressure drop models use a friction factor that is a function of the vapour Reynolds Number. For example, the Bravo-Rocha-Fair model uses:-

$$f = 0.177 + 88.774/Re_V$$

while the Stichlmair correlation uses:-

$$f = C_1/Re_V + C_2/\sqrt{Re_V} + C_3$$

where the three coefficients are fitted to dry pressure drop data for each packing type of interest.

In this study it has been found that, at general conditions, say above 10% of flooding, when $Re_L > 25$, the liquid will flow with waves over the packing, and the liquid/vapour interface is not smooth. The vapour velocities are sufficiently high that turbulent vapour flow exists, and the friction factor approaches a constant value. The experimental data can be fitted by using a constant friction factor that is corrected for the packing angle by using:

$$f = f_{45} \, [\sin 45/\sin\theta]^{1.2}$$

where θ is the packing angle. It has been found that the performance of the simple one-parameter model is as good as that of the previously published models.

It has also been found that the overall friction factor is influenced by column diameter due to wall effects. One effect is caused by the inherent space between the column wall and the packing. There is a relatively larger "open" wall area along the wall for small diameters versus large diameter columns. On the other hand, smaller diameter columns will introduce more vapour-direction turns. This increases the friction factor, and is dependent on element height and packing angle. For packing angles of 45 degrees, the diameter where this becomes significant is equal to the element height. In addition, the friction of the vapour against the column wall can no longer be neglected. The overall effect is that the pressure-drops are greater in smaller columns. However, it is difficult to determine exactly how the column diameter influences the pressure drop. The diameter might affect the pressure drop in the pre-loading regime differently from that in the loading regime. It also seems likely that the effect will depend on the size of the gap between the wall and the packing. The data on the various diameters of column considered here has shown this correction for column diameter to be necessary.

A simple model to account for the effect of diameter on the pressure drop combines the friction factor for the packing with a friction factor for the wall according to the area ratio, α, the area of the packing and the gap between the wall and the packing.

$$f_{45} = \alpha \, f_{pack} + (1 - \alpha) \, f_{wall}$$

For "dry" packing tests in a 4 inch diameter column the packing friction factor was 0.5 compared with 0.44, the value for a 16 inch diameter column.

2. *Loading point and loading regime.*

In order to model the pressure drop in the loading regime, it is imperative to determine the actual loading point. Various methods have been proposed to find the loading point, see Kister (1992). Billet defines the loading point as the point as the point where the liquid hold-up starts increasing with gas velocity, which usually occurs at 70% of flood. A rule of thumb suggested by Fair et al. states that, for random packing, loading will occur at pressure-drops above 0.5 inches of water per foot of bed (125 Pa/m). This last definition seems to apply approximately in the data used here, although a range of 125 to 200 Pa/m is seen.

There have been methods proposed which are more fundamentally based, for example one based on two-phase flow theory in vertical pipes (Taitel et al., 1980) and another based on Helmholtz instability theory (Carey, 1992). However, neither of these approaches provided a model satisfactory in all respects.

In order to predict the pressure drop in the loading region some previous models (e.g. Bravo et al.) have multiplied the dry packing pressure drop with a "loading" term that is a function of the liquid holdup:

$$[1/(1 - C_3 h_L)]^5$$

The use of this term increases the pressure drop exponentially as the liquid hold-up increases. However, this very rapid rise does not happen until the column starts flooding. Here we calculate the pressure drop in the loading regime by *adding* a second pressure drop term. It is postulated that this term is dependent on the weight of liquid that is suspended by the vapour. The fraction of liquid that is suspended is proportional to the F-factor of the effective vapour "lift" velocity. This is the difference in the effective vapour velocity at loading and at operating conditions. The loading pressure drop also scales with the density of the packing and the texture and geometry. A correlation has been developed for the Mellapak packing series. This model is quite different from other published models. It accounts for actual contributions of geometric parameters, and so it offers the possibility of identification of new packings based on changes to geometry that can reduce pressure drop or improve mass transfer. Since there are still empirical parts in the model developed for Mellapak packings, it is not known whether the model also applies to other packings.

3. *Liquid hold-up.*

Below loading the liquid hold-up equals the liquid hold-up in the film (Bird et al. p 40). The fractional liquid hold-up can be written as a function of the effective liquid Froude Number and Reynolds Number:-

$$h_L = [\mu_L a_p/(\rho_L U_{L,eff})]^{1/3} [3 U^2_{L,eff} a_p/g_{eff}]^{1/3} = [3 Fr_{L,eff} / Re_{L,eff}]^{1/3}$$

This approach was used in the new model In order to describe the increase in the total packing liquid hold-up, the film hold-up could be corrected by using a term which is proportional to the fraction of the liquid that is "suspended", i.e. proportional to the loading pressure drop.

Model Description.

As described above, the relative velocity between the liquid and the vapour is the key parameter in the model. Firstly, the effective velocities of liquid and vapour are calculated from the superficial velocities correcting for the liquid hold-up, packing angle and void fraction. The liquid is assumed to be present as a laminar liquid film flowing over the packing. The thickness of a falling film on an inclined surface is calculated by using the following equation (Bird et al., 1960, p40):-

$$\delta_{L,film} = \sqrt[3]{[3\ \mu_L U_{Ls} /(\rho_L\ a_p\ g \sin\theta\ \}]} \quad (1)$$

The liquid hold-up is calculated by multiplying the thickness by the nominal area, since it is assumed that the packing is completely wetted:

$$h_{L,film} = a_p\ \delta_{L,film} \quad (2)$$

The effective vapour and liquid velocities are then calculated by using:

$$U_{V,eff} = U_{Vs} /[(1 - h_{L,film})\ \varepsilon \sin\theta] \quad (3)$$

$$U_{L,eff} = U_{Ls} /[h_{L,film}\ \varepsilon \sin\theta] \quad (4)$$

where ε is the void fraction of the packing. If we know the packing area, packing sheet thickness (δ) and the fraction open area (φ), then the void fraction can be calculated from:

$$\varepsilon = 1 - [(1 - \varphi)\ \delta\ a_p]/2 \quad (5)$$

The relative effective velocity is the sum of the effective vapour and liquid velocities. The vapour relative F-factor is then computed using this velocity:

$$U_{R,eff} = U_{V,eff} + U_{L,eff} \quad (6)$$

$$F_{R,eff} = U_{R,eff} \sqrt{\rho_V} \quad (7)$$

The pressure drop below loading, where the liquid is flowing as a film over the packing, is then calculated using a simple Fanning type equation:

$$\{dp/dz\}_{film} = f\ F^2_{R,eff} /2s \quad (8)$$

with the friction coefficient, *f,* and the channel side, s. In order to account for the experimental data uncertainty, only one constant value is normally deemed necessary. The friction factor is most likely a packing-dependent parameter, and could be used to fit the pressure drop at low loading. On the other hand, *f* can be held constant and s could be used as a packing parameter. There is a potential problem with different packing angles, and the friction factor was adapted to allow for this:

$$f = f_{45}\ [\sin 45/\sin\theta\ ]^{1.2} \quad (9)$$

where $f_{45} = 0.44$. The effective relative velocity to predict the pressure drop flood point can be calculated using:

$$F_{R,eff,DPF} = \{1.58\sqrt{s}/\sigma^{0.4}\}\sqrt{[2(\rho_L - \rho_V)/\rho_L]}\ \sqrt[4]{[\sigma(\rho_L - \rho_V)g]} \quad (10)$$

The definition of the pressure drop flood point as 12 mbar/m is not fundamental. In fact, actual visual flooding often occurs at lower or higher loading. However, packing mass transfer efficiency often deteriorates before the visual flood point is reached.

The effective relative velocity at loading is calculated with an extension of this correlation. It was observed that the loading of the packing occurred at around 85% of the pressure drop flood point, except in the case of "foaming" mixtures, where it occurred at around 94%. This suggested a different dependence on surface tension:

$$F_{R,eff,load} = \{0.0035/(h_{L,film}\sqrt{\sigma})\}\sqrt{[2(\rho_L - \rho_V)/\rho_L]}\ \sqrt[4]{[\sigma(\rho_L - \rho_V)g]} \quad (11)$$

In order to model the increase in pressure drop due to the loading of liquid on the packing we use the difference between the effective vapour velocity and the effective vapour velocity at the loading point. The "loading" pressure drop is considered proportional to the F-factor of this difference velocity:

$$\{dp/dz\}_{load} = \{C_p/s^{1.75}\}F_\Delta\, g\sqrt{(\rho_L - \rho_V)} \quad (12)$$

$$F_\Delta = (U_{V,eff} - U_{V,eff,load})\sqrt{\rho_V} \quad (13)$$

The "loading" pressure drop is also dependent on the packing and is set to zero below the loading point. In order to scale the pressure-drops of the different packings we selected a scaling method based on the packing side dimension, since this was also used to fit the experimental data before loading. After determining the exponent of this parameter, the slope of the loading pressure drop was modelled with packing parameter C_p, (0.00213 for Mellapak 350YW and 0.00071 for Mellapak 500YL and 750YL). This difference is probably due to the packing surface textures. This parameter will probably be different.

Finally, the total pressure drop over the structured packing is the sum of the film and the loading pressure-drops:

$$dp/dz = \{dp/dz\}_{film} + \{dp/dz\}_{load} \quad (14)$$

where the "loading" pressure drop term is set to zero below the loading point, (as predicted from equation 11). A model for the liquid hold-up can be postulated from the pressure drop model. By using the new pressure drop model, the liquid hold-up above the loading point can be modelled by including a multiplier term for the film hold-up which is taken to be proportional to the F-factor used to determine the loading pressure drop:

$$h_L = h_{L,film}[1 + C_h F_\Delta] \quad (15)$$

where C_h has a value of 3.5. Equation (15) models the "backmixing" of liquid in the packing, and models the experimentally observed increase in liquid loading above the loading point, as observed by Suess & Spiegel (1992) for air/water tests on Mellapak 250Y and 500Y. The “backmixing” term in the liquid hold-up model can also be used to determine the point where the HETP increases. Above the loading point liquid droplets are formed, and these increase the interface area available for mass transfer. This counterbalances the negative effect of liquid backmixing in the packing. Only if the backmixing term becomes sufficiently large will the overall mass transfer decline.

For packings other than Mellapak the constants C_h and C_p will be different, as well as the constants in equations (10) and (11).

Model Implementation.

The first step in using the new model is to determine the loading and flooding velocities. To do this, the ratio of liquid and vapour velocities is fixed while the vapour velocity is varied, and the effective relative velocity calculated using equations (1) through (9). Once the vapour velocity at loading is calculated from equation (11), we can determine whether the loading pressure drop needs to be added. If so, the pressure drop is calculated from equations (12) through (14). Of course, the total pressure drop over a packed bed is the sum of the static vapour head and the dynamic packing pressure drop from equation (14), multiplied by the height of the bed.

Model Performance.

A large amount of experimental pressure drop data is available from measurements made in the Chemical Engineering laboratory in the University of Nottingham. These were made in a 150 mm diameter column, with a packed depth of about 850 mm. A detailed description of the experimental equipment used is given in Proctor et. al.(1998). Alcohol/alcohol mixtures were used, and measurements made with pure alcohols, both at total reflux and with a dry bed. In addition, measurements were made on the mixture n-Propanol/Water.

The comparison between the experimental results and the new model predictions are shown in Figures 2 to 8. It can be seen in Figure 2 that the modelling of both dry bed and operating pressure-drop is good. Figures 3-7 show the modelling of other alcohols and packing. Analysis of 44 experimental points shows a model prediction average relative error of 7.7%. Figure 8 shows the comparison with data on n-Propanol/Water. Here it can be seen that the modelling at low loadings is not good, and it is known (Biddulph & Krishnamurthy, 2001) that the surface tension of the liquid is just above the Critical Surface Tension for wetting of the packing surface. It is therefore likely that under-wetting and rivulet flow affected the observed pressure drop at low loading. The model prediction at higher loadings is much better, where the wetting is likely to have been much better.

The predictions from the new model have also been compared with experimental data from the 1.22 m diameter column at Fractionation Research Institute (FRI) and the 0.39 m column at Separation Research Program (SRP) at Austin, Texas. In both cases the data were obtained using Mellapak 250Y packing. Data from three different systems were available: iso-Butane/n-Butane at 6.9 bar pressure (FRI,

Figure 9), o-Xylene/p-Xylene at 0.13 bar (FRI, Figure 10) and Cyclohexane/n-Heptane at a pressure of 0.33 bar, (SRP, Figure 11). All tests were at total reflux. The open diamonds represent the experiments and the solid line represents the new model predictions. In Figures 9 and 10, which are shown with a logarithmic axis, the F-factor at loading and flooding, as predicted by the model, have been added with short and long dashed lines respectively. Also, the measured HETP values are shown as solid squares connected by a dashed line.

The new model predicts the pressure drop data with an average error of 6% for the SRP data and 25% for the FRI data (excluding points for certain “bad” distributors gives an error of 15%). It also performs well in predicting the loading point (where the HETP starts to increase) and the visual flood point (where the HETP becomes large).

Conclusions.

A new model for the prediction of structured packing pressure-drop performance has been developed. Its predictions have been compared with experimental data for Mellapak 250Y, 350Y, 500Y and 750Y grades of packing, under distillation conditions. It has been found to give good predictions of pressure drop both below and above the loading point. For the first time , both loading and flooding points are correlated, and can be calculated using the model.

Nomenclature.

a	area (m^2)
D	diameter (m)
h	liquid fractional hold-up (m^3/m^3)
f	friction factor (-)
F	F-factor, product of velocity and the square root of vapour density.
Fr	Froude Number.
g	gravitational constant, 9.81
n	number of elements in the packed bed.
p	pressure (Pa)
Re	Reynolds Number
s	packing side dimension (m)
U	velocity (m/s)
z	packing height (m)

Greek:

δ	thickness (m)
Δ	difference
ε	void fraction (m^3/m^3)
μ	viscosity (Pa.s)
θ	packing angle with horizontal (rad)
ρ	density (kg/m^3)
σ	vapour-liquid surface tension (N/m)

Subscripts:

c	column
eff	effective
film	film
L	liquid
load	loading
p	packing
R	relative
s	superficial
V	vapour

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