

A Phenomenological Model for Fluid-dynamics Evaluation of Structured Packing Systems

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A phenomenological model for the evaluation of pressure drop, liquid hold-up and capacity limit of structured packing systems is proposed. It is based on the analysis and evaluation of the different contribution to pressure drop and doesn't requires specific adaptive parameters for each type of packing like other models proposed in the literature. The model has been validated by comparison with a large amount of experimental data and the results are satisfactory.

1. Introduction

Structured packings are widely used in several vapor-liquid operations (e.g. absorption or distillation columns, sour gas scrubbing and stripping, catalytic distillation, petroleum refining operation etc.). High specific surface area, high mass-transfer coefficients and low pressure drops are characteristics of these packings. Geometrical characteristics vary with specific surface, corrugation angle, perforation etc. The accurate design of columns and optimal rating of equipments into which are used strictly depends on their fluid-dynamic behavior. Several researchers, like for instance J.L. Bravo et al. (1986), E. Brunazzi and A. Paglianti (1997), Huib-Jan Verschoof et al. (1999), J.R. Fair et al. (2000), Ion Iliuta and Faical Larachi (2001), Ion Iliuta et al. (2004), have developed mathematical models for the prediction of the fluid-dynamic behavior of structured packing. The models were often based on the interpretation of the main phenomena and the proposed mathematical expressions were then adapted to experimental data by means of parameters generated through the regression of a large number of them. For instance an excellent paper of J.R. Fair et al. (2000) compares two models; one has been developed by the Separations Research Program (SRP) of The University of Texas at Austin, the other one developed at Delft University. The first one is based on the use of a large number of specific parameters for each kind of packing and requires a collection of experimental data for their evaluation. For this reason the validity of this model is restricted to the conditions in which experiments have been performed. In the second one, several macro-geometry characteristics, affecting packing performance, have been explicitly incorporated into the model. Even in this case the model cannot be defined completely mechanistic because it needs parameters resulting from tuning a large number of experimental data. Other examples of developing mechanistic models are the paper of Brunazzi and Paglianti (1997) and Iliuta and Larachi (2001). In both the cases the evaluation of factors contributing to pressure drop is only partially developed. In the work of Iliuta and Larachi the attention is focused on

the problem of surface wetting. From the other hand, the work of Brunazzi and Paglianti requires the dynamic liquid hold-up for pressure drop evaluation. The present paper proposes a phenomenological model which minimizes regression parameters. The model is based on the individuation of five main contributions to pressure drop, loading and flooding limits and of course liquid hold-up.

2. Contributions to pressure drop in the system

The contributions to pressure drop in the system belong to two main classes: the contributions that are present also in absence of liquid and those that are due to the interaction of the gas with the liquid film. The texturing of the crimp surface helps the complete wetting of the packing. Eventually only at very low liquid rates incomplete wetting can appear.

2.1 Channels pressure drop

The fluid crosses several packing elements moving along the channels formed by the corrugations. At every change of element the fluid suddenly modifies the direction of flow. Consequently the fluid-dynamic pattern here corresponds to that typical of the tubes entrance region (i.e. a boundary layer develops along the channel surface). This phenomenon is not present in High Capacity packings (HC) thanks to the smooth bends of crimps at the ends of the elements. The expression for this contribution is, in the case of Non High Capacity (NHC) and HC packing:

$$\text{NHC} \quad f = 30 \frac{D_i \sin \theta}{4ht} \left[\arctan \sqrt{2} - \arctan \left\{ 2 - 4.2 \sqrt{ht / (D_i \sin \theta \cdot Re_G)} \right\} / \sqrt{2} \right] \quad 1)$$

for $ht / (D_i \sin \theta \cdot Re_G) \leq 0.056$

$$\text{HC} \quad \begin{aligned} f &= 16 / Re_G & \text{for } Re_G \leq 2500 \\ f &= 0.079 \cdot Re_G^{-0.25} & \text{for } Re_G > 2500 \end{aligned} \quad 2)$$

The pressure drop referred to unit height therefore is given by:

$$\frac{\Delta P_1}{L} = 2f \frac{[G_{G0} + \text{par}]^2}{\rho_G \sin \theta \cdot D_i} \quad 3)$$

where “par” accounts the average interface velocity of the film:

$$\text{par} = \rho_G \left[\frac{(\Delta \rho \cdot g \cdot \sin \theta \cdot s^2)}{(2\mu_L)} - (\tau \cdot s D_h) / (\mu_L D_i)^2 \right]$$

2.2 Pressure drop due to the crimps crossing

Another important contribution depends on gas-gas interaction resulting at channel crossing. Because the moving direction is not parallel, a mixing layer is generated and the following expression can be deduced by extension of the boundary layer theory:

$$\frac{\Delta P_2}{L} = 13.5 (1 - f_h)^2 (\cos^2 \theta) \left[(G_{G0} + \text{par})^2 \cos^{2.5} \theta \right] / \left\{ \rho_G D_i \sin^{0.5} \theta \cdot [1.4 Re_G]^{0.5} \right\} \cdot \frac{4}{D_i} \quad 4)$$

The formula shows that in the case of perforated sheets the holes offer a “way of escape” for the vapor reducing the contribution to pressure drop caused by the crossed flows.

2.3 Pressure drop due to impact on the column wall

The impact of the gas flow on the column wall surface produces another contribution to pressure drop that can be of some importance in the case of small diameter columns. This effect regards only a fraction of the packing element characterized by an average

$$\text{effective length of: } \bar{l}_{\text{eff}} = \frac{4}{\pi} \frac{ht}{\sin \theta} \left\{ \frac{\pi}{4} - \frac{ht}{2D_c \tan \theta} \right\}$$

The pressure drop per unit height can be calculated as follows:

$$\frac{\Delta P_3}{L} = \frac{2}{\pi} \frac{(G_{G0} + \text{par})^2 \cos \theta}{D_c \tan \theta} \left[\omega_{\text{cr}} + \sin \omega_{\text{cr}} \cdot \cos \omega_{\text{cr}} + \frac{D_c}{3ht} \tan \theta (2 - 3 \sin \omega_{\text{cr}} + \sin^3 \omega_{\text{cr}}) \right] \quad 5)$$

where: $\omega_{\text{cr}} = \arccos[ht/(D_c \tan \theta)]$

2.4 Pressure drop due to elements intersection

In the most diffused packings, at elements intersection, the vapor flow changes suddenly the direction between two adjacent elements and the crest of the liquid wave can lift and fall down, producing a local recycle of extra-flowrate. The extension of this recirculation region is in the order of magnitude of 3 hydraulic diameters (corresponding to about 3 wave lengths). The additional flow-rate can be evaluated by using equation 6:

$$G_{L,\text{add}} = [\rho_L (G_{G0} + \text{par}) 4\alpha s D_i] / [\rho_G \pi D_h^2 \sin(2\theta)] \quad 6)$$

The pressure drop is calculated from the following expression (for NHC):

$$\frac{\Delta P_4}{L} = G_G^2 \frac{\sin(2\theta)}{ht\sqrt{2}} \left/ \left[\rho_G \left(1 - \frac{2s_{L,\text{add}}(1+\alpha)}{D_h} \right)^4 \right] \right. \quad 7)$$

In the case of HC the loss is due only to the smooth change in flow direction and is evaluated as follows:

$$\frac{\Delta P_4}{L} = G_G^2 \frac{2\cos(\theta)}{ht\sqrt{2}} \left/ \left[\rho_G \left(1 - \frac{2s(1+\alpha)}{D_h} \right)^4 \right] \right. \quad 8)$$

This region is mostly critical for loading and flooding conditions.

2.5 Effects of capillary waves

The film moves forming capillary waves. Their length and amplitude can be deduced starting from the theory of Kapitza (V.G. Levich, 1962) extended to the case of the presence of a gas interacting with the liquid. The waves produce restriction and expansion of the flow section and the pressure drop can be deduced starting from the formula of Borda. After some elaborations it is possible to obtain:

$$\tau_{\text{waves}} = \left[\left\{ G_G^2 / (2\rho_G) \right\}^{3/2} 6(\alpha \cdot s)^{3/2} \right] \left/ \left\{ \left[1 + \frac{2 \cdot \alpha \cdot s}{D_i} \right]^4 \left[1 - \frac{2 \cdot \alpha \cdot s}{D_i} \right]^6 \pi \sigma^{1/2} (D_i) \right\} \right. \quad 9)$$

where: α = function depending on vapor flow-rate, ranging from 0.21 to 1 (loading condition): $0.21 + 0.79 G_G / G_{G,load}$. Therefore the pressure drop is given by:

$$\frac{\Delta P_5}{L} = \tau_{waves} \frac{4}{D_i} \quad (10)$$

The average film thickness can be easily deduced from the theory related to the action of gas on the interface. This last is constituted by the contribution 1,2 and 4 along the crimp length. At the overlap of elements also the fifth contribution is present together with an increased liquid flow due to accumulation. The film thickness is obtained from the following equation:

$$s^3 \left(\frac{\rho_L \Delta \rho g \cdot \sin \theta}{3\mu_L} - \frac{4\tau_G \rho_L}{3\mu_L D_i} \right) - \frac{\rho_L \tau_G s^2}{2\mu_L} - \frac{G_L D_h}{4} = 0 \quad (11)$$

3. The loading and flooding conditions

Physically the loading condition corresponds to a film interfacial velocity equal to zero. The corresponding vapor flow-rate, deduced by using once again the liquid film theory is:

$$G_{G,load} = \left[\tau_{G,load} / \left(\alpha + \beta + \gamma \frac{(G_{G0,load} + par)^3}{G_{G0,load}^2} \right) \right]^{0.5} \quad (12)$$

where: $\alpha = f/2\rho_G \sin \theta$

$$\beta = 13.5(1 - f_h)^2 (\cos^2 \theta) \left[G_{G0}^2 \cos^{2.5} \theta \right] / \left\{ G_G^2 \rho_G D_i \sin^{0.5} \theta \cdot \left[1.4 G_{G0} D_i / \mu_G \right]^{0.5} \right\}$$

$$\gamma = 6 \left(\frac{1}{2\rho_G} \right)^{3/2} (G_{G0,load} + par)^3 s_{load}^{1.5} / \left\{ \pi \sigma^{0.5} \left(1 - 2 \frac{s_{load}}{D_i} \right)^6 \left(1 + 2 \frac{s_{load}}{D_i} \right)^4 D_i G_{G,load}^2 \right\}$$

(α , β , and γ are related to the different contributions to pressure drop).

Contrary to loading situation, flooding is theoretically more difficult to be evaluated. It occurs when the vapour is able to sustain the weight of the liquid. In this condition liquid becomes part of a froth occupying 25-30% of the available volume. (for HC the constant 1.76 is replaced by 1.2):

$$NHC: G_{G,flood} = G_{G,load} \cdot \left(\frac{0.25 \sin^2 \theta}{1 + 1.76 \frac{D_h}{ht}} \cdot \left(\frac{\varepsilon \rho_L \Delta \rho g \sin \theta D_h^2}{3\mu_L G_L} \right)^{1/3} \right)^{1/35} \left[G_L^2 / \varepsilon^2 g D_h \Delta \rho^2 \right]^{0.2} \quad (13)$$

The pressure drop in the range from loading to flooding point has been estimated by means of an interpolation:

$$\Delta p/L = (\Delta p/L)_{load} \left(G_G / G_{G,load} \right)^{35} \left[G_L^2 / \varepsilon^2 g D_h \Delta \rho^2 \right]^{0.2} \quad (14)$$

4. Comparisons

The model has been compared with a large number of experimental data relevant to different packings, operating conditions and fluids. For lacking of space just six examples of pressure drop are reported. The experimental data derive from the papers of Huis-Jan Verschoof et al. (1999) and James Fair et al. (2000). All the comparisons are satisfactory. In fig.1,2,3 D_C is 0.43 m and bed height 3.4m. In fig. 4 D_C is 1.2 m column and bed height 4m. Extended good results are also obtained for liquid hold-up.

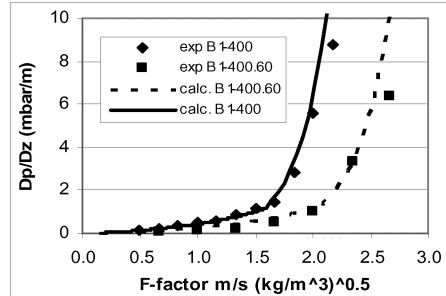


Figure 1: Comparison of experimental and calculated Montz-PAK type B1-400 pressure drop. Corrugation angle effect. Cyclohexane/n-heptane. Total reflux.

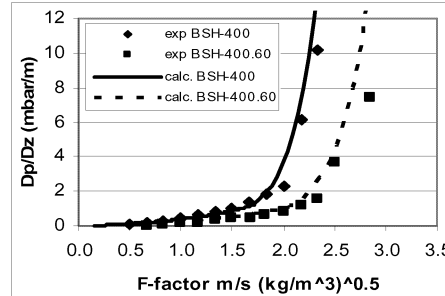


Figure 2: Comparison of experimental and calculated Montz-PAK type BSH-400 pressure drop. Corrugation angle effect. Cyclohexane/n-heptane. Total reflux.

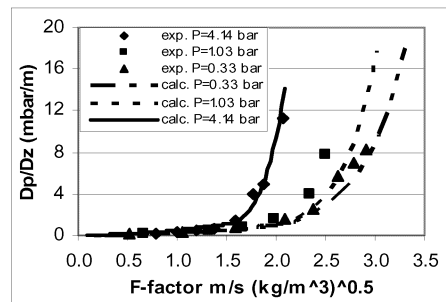


Figure 3: Comparison of experimental and calculated Montz-PAK type B1-250 pressure drop. Pressure effect. Cyclohexane/n-heptane. Total reflux.

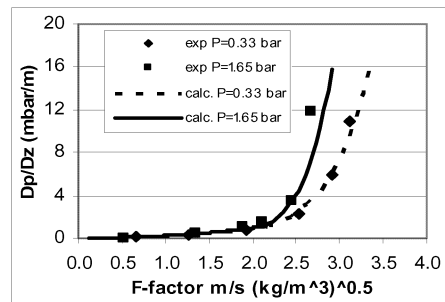


Figure 4: Comparison of experimental and calculated Montz-PAK type BSH-250 pressure drop. Pressure effect. Cyclohexane/n-heptane. Total reflux.

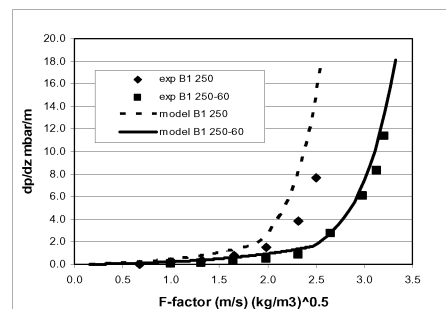


Figure 5: Comparison of experimental and calculated Montz-PAK type B1-250 pressure drop. Corrugation angle effect. Cyclohexane/n-heptane. Total reflux.

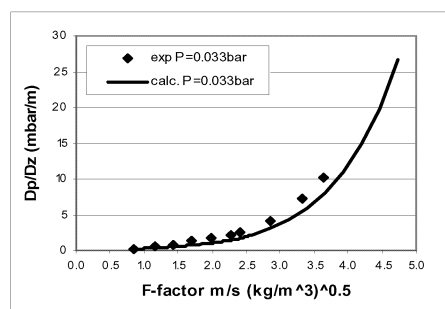


Figure 6: Comparison of experimental and calc. Gempak 2AT pressure drop. Chlorobenzene/ethylbenzene. Column diameter 0.22 m, bed height 2 m. Total reflux.

5. Conclusions

The proposed model is based on the deep analysis of all the contribution to pressure drop in structured packing systems. It can be used for different kinds of corrugated packings, also for the HC ones, and for different operating conditions. The comparisons with the experimental data confirm the validity of the proposed model.

6. Nomenclature

a_p = packing specific surface (m^2/m^3)
 D_C = column diameter (m)
 D_h = hydraulic diameter (m) = $4 \cdot \varepsilon / a_p$
 D_i = hydraulic diameter depurated from liquid film thickness (m)
 f_h = fraction of surface area occupied by holes
 g = gravitational acceleration (m/s^2)
 G = specific flow-rate (kg/m^2)
 G_{G0} = vapor specific flow-rate into channels = $G_G / \left[\varepsilon (D_i / D_h)^2 \right]$ (kg/m^2)
 $G_{L,add}$ = additional specific liquid flowrate at elements overlap (kg/m^2)
 ht = height of the packing element (m)
 Re_G = vapor Reynolds number = $(G_{G0} + par) D_i / \mu_G$
 s = liquid film thickness (m)
 $s_{L,add}$ = liquid film thickness in the region of element overlap (m)
 ε = packing void fraction
 θ = inclination angle of the corrugation with respect to the horizontal
 μ = viscosity (Pa s)
 ρ = density (kg/m^3)
 $\Delta\rho$ = difference in density between liquid and vapour (kg/m^3)
 σ = surface tension (N/m)
 τ = shearing stress (N/m^2)
 τ_{waves} = shearing stress due to capillary waves (N/m^2)
 G = index for vapor
 L = index for liquid
 load = index for loading condition

7. References

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