Mechanistic Pressure Drop Model for Columns Containing Structured Packings

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A mechanistic model was developed to predict pressure drop and flooding in packed columns equipped with corrugated packing of the regular type. It was developed after considerating the interaction of falling liquid film with the gas phase, based on mass- and momentum-conservation equations. Among the most common structured packings, the behavior of the Mellapak and BX types was analyzed. The aim of this work is to demonstrate how mechanistic models, developed for simple geometry, can also be used to compute pressure drops in cases where the geometry is more complex, as with a structured packing. This approach, based on the geometric characteristics of the packing and measurable parameters such as liquid holdup, enables the development of a basic model by limiting the number of adjustable parameters, which are numerous in all the available models. Because of its nature, this model is extremely easy to extend to different types of structured packings.

Introduction

In the last few years, increased attention has been devoted to optimizing the absorption process, due partly to increased sensitivity to environmental pollution. Hence, researchers and manufacturers have studied and developed new types of column interiors. Among these interiors, corrugated packings of the regular type, also called structured packings, have received the greatest attention owing to their favorable performance. It is well recognized, in fact, that regular packings make it possible to minimize pressure drop per theoretical stage by allowing a reduction in energy consumption (Brunazzi et al., 1996).

Structured packings can be made of plastic or metallic materials, depending on the application. From the geometric point of view, the packings are made of corrugated sheets or gauzes arranged in parallel, successive layers having an opposite angle of corrugation, as shown in Figure 1. Flow channels resulting from this arrangement are inclined at an angle of 60 or 45 deg to the horizontal. To promote turbulence the surfaces of the layers are often embossed and grooved. The particular form of the packing makes it possible to obtain a highly specific surface (250 m^2/m^3 or 500 m^2/m^3 in the most commonly used packings; these values do not take into ac-

Figure 1. Structured packing.

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count the additional area provided by the surface structure) with truly minimal reduction in free volume—about 2%.

One drawback in the use of regular packings is their high cost per unit volume and thus the high capital investment required for columns equipped with these materials compared with columns containing common dumped packings. Therefore, for correct design it is necessary to evaluate both investment and operating costs in order to choose the type of interior with the least total cost. While with random packings the overestimation in the design of a column results in only a small increase in the investment cost, this is not true for columns equipped with structured packings. A reliable design model is therefore necessary.

One can find many systematic studies in the literature on mass transfer and pressure drops in columns equipped with random packings, whereas there are few published reports on modern structured packings. This is a serious lack because it has been estimated that 25% of all refinery vacuum towers worldwide are equipped with this new type of packing.

Another favorable characteristic of structured packings, discussed by Billet (1989) and confirmed in various reports, is that, if carefully installed, these packings make it possible to reduce problems linked to maldistribution that are often observed in conventional beds of packings. These characteristics explain why these packings are applied in most operations in the chemical industry, such as the distillation of amines, glycols, higher fatty alcohols, acids, and methanol as well as in the production of heavy water.

The potential use of this equipment is really extensive, but so far, columns equipped with this type of interior are designed using semiempirical equations with uncertain limits of application. Until now the approach commonly followed by various workers has been to develop distinct models to predict pressure drop (Stichlmair et al., 1989; Bravo et al., 1986; Billet, 1989; Rocha et al., 1993; Robbins, 1991; Spiegel and Meier, 1992) and mass-transfer efficiency (Bravo et al., 1985; Spiegel and Meier, 1987; Brunazzi et al., 1995; Nardini et al., 1996). Recently, Bravo et al. (1992) proposed a comprehensive model that allows global evaluation of the performance of columns equipped with this type of interior. The proposed model has been used with acceptable results but, because of the large number of adjustable parameters, its application in ranges outside the tested region can lead to sizable errors.

In the present work a simple model to compute pressure drop in a column in which gas and liquid flow countercurrently, or also cocurrently, has been developed. The model is based on estimation of the wetted surface of the packing, in accordance with previous works by the present authors concerning mass transfer, and on the application of momentum and mass-conservation equations.

Mechanistic Model

In columns equipped with structured packings the liquid flows on the surface of each layer as thin film, while the gas flows through the channels contacting the liquid in such a way that it can be considered similar to a wetted wall arrangement. Due to the geometric and hydrodynamic characteristics, and according to previous work concerning mass transfer in structured packings (Brunazzi et al., 1995; Nardini et al., 1996), channels within the packing have been drawn as a bundle of columns with a circular cross section, inclined with respect to the horizontal axis by an angle equal to the angle formed by the corrugation with the same axis. The characteristic dimension of the flow channel, as proposed by Shi and Mersmann (1985) and adopted by Billet and Schultes (1993), is defined as

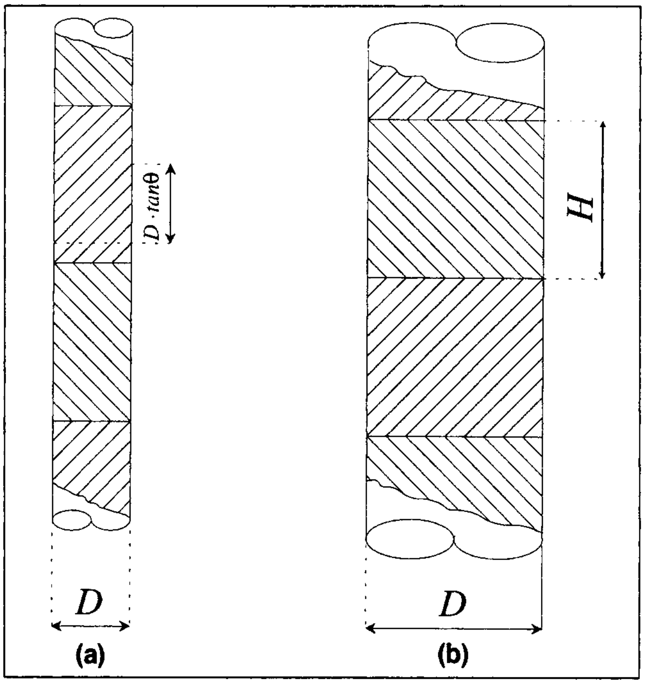

Figure 2. Flow channels within the packing.

$$d_e = \frac{4 \cdot e}{a_g}, \tag{1}$$

where void fraction, e, and specific surface area, a_g, are the geometric parameters of the packing. According to the packing scheme just described and shown in Figure 2, friction losses arising from the flow of the gas phase through the column can be attributed to two terms. The first term takes into account distributed losses at the channel walls and at the gas–liquid interface, while the second term considers concentrated losses resulting from changes in the flow directions,

$$\left(\frac{dP}{dx}\right)_F = \left(\frac{dP}{dx}\right)_{F,d} + \left(\frac{dP}{dx}\right)_{F,c}. \tag{2}$$

The pressure gradient per unit height of column is then given by the sum of the frictional, gravitational, and acceleration terms,

$$\left(\frac{dP}{dx}\right)_{TOT} = \left(\frac{dP}{dx}\right)_F + \left(\frac{dP}{dx}\right)_G + \left(\frac{dP}{dx}\right)_A. \tag{3}$$

The detailed expression for each term in the dry case as well in the irrigated case is examined in the following sections.

Dry pressure drop

Without liquid flowing in the column, the acceleration term can be expressed as

$$\left(\frac{dP}{dx}\right)_A = \rho_g \cdot U_{sg} \cdot \frac{dV_b}{dx}, \tag{4}$$

the effective gas velocity in the channel, V_b, may be computed from the superficial gas velocity, U_{sg}, taking into account packing void fraction, e, and inclination angle, ϑ,

$$V_b = \frac{U_{sg}}{e \cdot \sin\vartheta}. \tag{5}$$

The gravitational term is computed, considering incompressible flow, by

$$\left(\frac{dP}{dx}\right)_G = \pm \rho_g \cdot g, \tag{6}$$

where $\pm$ is relative to upward or downward flow.

The distributed frictional term may be computed by a momentum balance on the gas flow in a single channel:

$$\left(\frac{dP}{dx}\right)_{F,d} = \frac{1}{A_g \cdot \sin\vartheta}(\tau_{wg} \cdot S_g), \tag{7}$$

where A_g is the cross-sectional area of the channel available for the gas phase and S_g is the channel perimeter wetted by the gas. In the dry case, these two terms are given by

$$A_g = \frac{\pi \cdot d_e^2}{4}, \tag{8}$$

$$S_g = \pi \cdot d_e, \tag{9}$$

while τ_{wg} is the shear stress at the channel wall relative to the gas phase flowing alone in the channel and is defined as

$$\tau_{wg} = \frac{1}{2} \cdot f_g \cdot \rho_g \cdot V_b^2, \tag{10}$$

where the gas friction factor, f_g, is a function of the Reynolds number of the gas phase (see Eq. 15).

The concentrated term is computed by

$$\left(\frac{dP}{dx}\right)_{F,c} = 4 \cdot f_g \cdot N_c \cdot \left(\frac{L_{eq}}{d_e}\right) \cdot \frac{\rho_g \cdot V_b^2}{2}, \tag{11}$$

where L_{eq} is the length of the channel giving a pressure drop equivalent to that arising from the change in the flow direction due to each single bend, and N_c is the number of flow direction changes in a unit height of the packing.

Thus, the frictional dry pressure drop for unit height of packing may be summarized by the following relationship:

$$\left(\frac{dP}{dx}\right)_F = 4 \cdot f_g \cdot \left(\frac{1}{d_e \cdot \sin\vartheta} + N_c \cdot \frac{L_{eq}}{d_e}\right) \cdot \frac{\rho_g \cdot V_b^2}{2}. \tag{12}$$

Besides the operating conditions and geometric characteristics of the packing, the parameters necessary to evaluate the frictional pressure drops, by means of Eq. 12, are the ratio between the equivalent channel length of each bend and the characteristic dimension of the channel, L_{eq}/d_e, the number of bends per unit height of packing, N_c, and the gas frictional factor, f_g. The term L_{eq}/d_e is related to the corrugation angle of the packing; the value given to this parameter must decrease, increasing the angle of the bend with respect to the horizontal axis. The following values were adopted (Boucher and Alves, 1973): 25 for a 60-deg corrugation angle, corresponding to a bend giving a change in the flow direction of 120 deg, and 35 for a 45-deg corrugation angle, corresponding to a change in the flow direction of 90 deg. The number of bends in a unit height of packing, N_c, depends on the packing element height, H, and the column diameter, D. According to Figure 2, if the column has a small diameter (Figure 2a), then the number of bends is related to both column diameter and inclination angle, whereas if the column diameter is large (Figure 2b), the number of bends per unit of packing height depends only on the element height. According to this scheme, it follows that
if

$$D \leq \frac{H}{\tan\vartheta},$$

then

$$N_c = \frac{1}{D \cdot \tan\vartheta} \quad \text{(a)} \tag{13}$$

whereas if

$$D > \frac{H}{\tan\vartheta},$$

then

$$N_c = \frac{1}{H}. \quad \text{(b)} \tag{14}$$

This approach explains the reason for lower pressure drops measured experimentally when, operating at constant specific gas and liquid loadings, columns with increasing diameters are used (Sulzer, 1991).

Assimilation of the flow channels within the packing to a bundle of identical columns has led to Eq. 12 for the evaluation of the friction losses due to the gas flow in the packing. This expression is similar to the one usually adopted for flow in pipes. The friction factor depends on the Reynolds number of the gas and the roughness of the channel walls. Bravo et al. (1986) showed that the channel-wall friction factor in structured packings, for both laminar and turbulent conditions, can be correlated by the following general relationship:

$$f_g = B1 + \frac{B2}{Re_g}. \quad (15)$$

The same type of dependence on the Reynolds number of the gas phase has been assumed in this work by defining the dimensionless number as

$$Re_g = \frac{\rho_g \cdot V_b \cdot d_g}{\mu_g}, \quad (16)$$

where d_g is the equivalent diameter for gas flow

$$d_g = \frac{4 \cdot A_g}{\pi \cdot d_e}, \quad (17)$$

and it coincides, for the dry case, with the characteristic dimension of the packing. Constants $B1$ and $B2$ appearing in Eq. 15 depend on the particular packing type, and their evaluation results from fitting the experimental values of dry pressure drop.

The turbulent friction factor for flow in pipelines can be computed by Colebrook's equation, applied to hydraulically rough pipes (Cheremisinoff, 1983), which relates friction factor to absolute roughness and pipe diameter. According to this equation, in the present work the following relation has been derived to compute the friction factor, f'_g, for a structured packing whose equivalent channel diameter is d'_e, from knowledge of the friction factor f_g, measured using a structured packing whose equivalent channel diameter is d_e

$$f'_g = \left(\frac{1}{\sqrt{f_g}} + 4 \cdot \log_{10} \frac{d'_e}{d_e} \right)^{-2}. \quad (18)$$

It must be underscored that this approach can be followed only if both packings display the same absolute roughness.

Irrigated pressure drop

In this work a theoretically based approach, similar to those developed for simple geometry like transport pipelines, has been adopted, making it possible to compute pressure drop in packed columns in spite of the more complex geometry. The pressure gradient is computed, as for the dry case, by summing gravitational, accelerational, and frictional terms. The liquid phase can flow cocurrently or countercurrently with respect to the gas phase, and in both cases the present model assumes that the two-phase flow pattern is *separate*, with the liquid phase flowing on the bottom of each channel and the gas phase above it.

The first problem to solve in the presence of liquid flow is identifying the part of the structured packing that is actually wetted by the liquid phase. The reason for this is that, according to the present hydraulic model, shear stresses both at the channel walls and at the gas–liquid interface contribute to the frictional losses, and to evaluate them, knowledge of both the gas–liquid interfacial area and of the unwetted fraction of the channel wall is necessary. As shown by Brunazzi et al. (1995) for Mellapak packing, and by Nardini et al. (1996) for BX packing, this information is related to the dynamic liquid holdup measured in the absence of the gas load. The starting point of those models is the assumption that the liquid phase flows on the structured packing as a falling film. If the liquid is Newtonian and the flow is laminar, it is possible to compute the liquid thickness, and from this value, together with the liquid holdup, the surface of the structured packing that is effectively wetted by the liquid phase. According to these assumptions, it follows that:

$$\frac{a_e}{a_g} = \left(\frac{d_e \cdot \sin\vartheta}{4 \cdot e} \right) \cdot (h_l)^{1.5} \cdot \left(\frac{\rho_l \cdot g}{3 \cdot \mu_l \cdot U_{sl}} \right)^{0.5}, \quad (19)$$

where a_e is the effective wetted surface, a_g the geometric surface, h_l the dynamic liquid holdup (Nardini et al., 1996), and U_{sl} the superficial liquid velocity.

As for the dry case, acceleration, gravitational, and frictional terms will be analyzed. The acceleration term is related to gas expansion effects and can be expressed by Eq. 4, where V_b must take into account the presence of the liquid phase, and can be computed as

$$V_b = \frac{U_{sg}}{(1 - h_{l,c}) \cdot e \cdot \sin\vartheta}, \quad (20)$$

where $h_{l,c}$ is the dynamic liquid holdup with reference to the channel and is related to the liquid holdup in the column by means of the simple relation (Brunazzi et al., 1995),

$$h_l = h_{l,c} \cdot e. \quad (21)$$

If the gas mass flow is constant, the accelerational term becomes

$$\left(\frac{dP}{dx} \right)_A = -\left(\frac{\rho_g \cdot U_{sg}^2}{(1 - h_{l,c})^2 \cdot e \cdot \sin\vartheta} \right) \cdot \frac{dh_{l,c}}{dx} + \frac{U_{sg}^2}{(1 - h_{l,c}) \cdot e \cdot \sin\vartheta} \cdot \frac{d\rho_g}{dx}, \quad (22)$$

this term may be neglected when liquid holdup and gas density are assumed to remain constant along the column, as may be hypothesized for low values of pressure drop. Since the gravitational term can be expressed as shown in Eq. 6, the last term that must be evaluated is the frictional one.

The distributed term derives from the momentum balance relative to the gas phase and can be written in the following form:

$$\left(\frac{dP}{dx} \right)_{F,d} = \frac{1}{A_g} \cdot (\tau_{wg} \cdot S_g + \tau_i \cdot S_i) \cdot \frac{1}{\sin\vartheta}, \quad (23)$$

where A_g, the cross-sectional area available for the gas flow, can be computed as

$$A_g = \frac{\pi \cdot d_e^2}{4} \cdot (1 - h_{l,c}), \quad (24)$$

and S_g is the perimeter of the single channel affected by the gas phase, S_i is the length of interfacial chord, and τ_i and τ_{wg} are the shear stresses at the gas–liquid interface and at the wall, respectively. The shear stress at the channel wall is defined, as in the dry case, by Eq. 10, whereas the interfacial shear stress is computed by

$$\tau_i = \frac{1}{2} \cdot f_i \cdot \rho_g \cdot (V_b \pm V_l)^2, \tag{25}$$

where $\pm$ is relative to the countercurrent or cocurrent configuration and the effective liquid velocity, V_l, can be calculated as

$$V_l = \frac{U_{sl}}{h_{l,c} \cdot e \cdot \sin\vartheta}. \tag{26}$$

As in the dry case, the concentrated term can be evaluated by

$$\left(\frac{dP}{dx}\right)_{F,c} = 4 \cdot f_m \cdot \frac{L_{eq}}{d_e} \cdot N_c \cdot \rho_g \cdot \frac{V_b^2}{2}, \tag{27}$$

where the friction factor f_m derives from a mean, weighted on the wetted area, between the wall friction factor, f_g, and the interfacial friction factor, f_i.

Finally, pressure drops are essentially functions of the effective gas and liquid velocities. Because of the complex geometry, to compute these quantities, it is necessary to know the superficial liquid and gas velocities, the length of the interfacial chord, and the thickness of the film flowing in each channel. The liquid and gas loads are the working conditions of the column, whereas the interfacial chord, S_i, and the channel perimeter affected by the gas flow, S_g, are simple functions of the wetted surface a_e:

$$S_i = \frac{a_e}{a_g} \cdot \pi \cdot d_e, \tag{28}$$

$$S_g = \pi \cdot d_e - S_i. \tag{29}$$

In the present work we have assumed that the length of the interfacial chord is equal to the length of the channel perimeter wetted by the liquid. We have also assumed that the wetted area is not significantly influenced by the gas load, as suggested by Bravo et al. (1992) and Henriquez de Brito et al. (1994). Thus S_i and S_g depend exclusively on the liquid load and can be computed by applying the relation for the ratio of the wetted area to the geometric specific area, as suggested by Brunazzi et al. (1995) and Nardini et al. (1996), and given by Eq. 19.

The parameter that remains to be evaluated is the thickness of the falling film. For this purpose, if the gas and liquid effective velocities remain constant along the column, the momentum equation on the falling liquid film can be written as

$$\frac{\partial \tau_{zy}}{\partial z} = \rho_l \cdot g \cdot \sin\vartheta \mp \left(\frac{dP}{dy}\right)_{\text{chan}}, \tag{30}$$

where $\mp$ refers to the countercurrent or cocurrent configuration. If the liquid is Newtonian and flows in laminar conditions, it is possible to integrate this equation, obtaining the film thickness

$$\delta = \frac{\pm \dfrac{\tau_i}{2 \cdot \mu_l} + \sqrt{\left(\pm \dfrac{\tau_i}{2 \cdot \mu_l}\right)^2 + 4 \cdot \left[\rho_l \cdot g \cdot \sin\vartheta \mp \left(\dfrac{dP}{dy}\right)_{\text{chan}}\right] \cdot \dfrac{V_l}{3 \cdot \mu_l}}}{\dfrac{2}{3 \cdot \mu_l} \cdot \left[\rho_l \cdot g \cdot \sin\vartheta \mp \left(\dfrac{dP}{dy}\right)_{\text{chan}}\right]}, \tag{31}$$

where

$$\left(\frac{dP}{dy}\right)_{\text{chan}} = \left(\frac{dP}{dx}\right)_{F,d} \cdot \sin\vartheta \pm \rho_g \cdot g \cdot \sin\vartheta. \tag{32}$$

To solve the model it is necessary to compute the friction factors f_g and f_i. The first factor can be obtained from the analysis of dry pressure drops, as described in the previous section (see Eqs. 12 and 15), while a detailed analysis follows for the second factor. Several works on the two-phase cocurrent flow in vertical pipes can be found in the literature, whereas fewer works have been published on the countercurrent scheme. In one of these latter works, Bharathan (1978) showed that the correlation developed by Wallis (1969) greatly underpredicts the interfacial friction factor when it is applied to countercurrent flow close to the flooding point, and suggested the following relation

$$f_i = 0.005 \cdot \left[1 + p \cdot \left(\frac{\delta}{d}\right)^q\right], \tag{33}$$

where p and q are functions of the pipe diameter, d. This equation has limited validity because it does not take account of the physical properties of the working fluids. According to the suggestions given by both Willets (1987) and Andreussi (1990), it seems more correct to introduce a dependency on the physical properties of the working fluids, so in this work the relation proposed by Bharathan (1978) has been changed, giving the following final form for countercurrent flow:

$$f_i = f_g \cdot \left[1 + B3 \cdot Bo^{0.3} + B4 \cdot \left(\frac{\delta - \delta_0}{d_e}\right) \cdot \left(\frac{\mu_l}{\mu_{l,0}}\right)^{0.1} \cdot We_l^{\alpha}\right], \tag{34}$$

where Bo and We_l are, respectively, the Bond and Weber numbers for the liquid phase:

$$Bo = \frac{d_l^2 \cdot g \cdot (\rho_l - \rho_g)}{\sigma_l}, \qquad We_l = \frac{\rho_l \cdot V_l^2 \cdot d_l}{\sigma_l}, \tag{35}$$

with d_l the equivalent diameter for the liquid phase defined as

Table 1. Characteristic Constants of Eqs. 15 and 34

Type of Packing	Material	B1	B2	B3	B4	α
Mellapak 250Y	Metal	0.0178	6.2	0.348	700	0.4
Mellapak 250Y	Plastic	0.023	9	4.4	180	0.4
Mellapak 250X	Metal	0.0178	6.2	0.871	700	0.6
BX	Metal	0.032	4.7	1.741	170	0.6
BX	Plastic	0.042	18	1.741	170	0.6

$$d_l = 4 \cdot \delta. \tag{36}$$

Values for coefficients B3, B4, and α are given in Table 1 for the types of structured packing that have been examined in this work. The second term in square brackets of Eq. 34 takes into account the presence of the liquid phase for low gas loadings, while the third term takes into account the effect of increasing film thickness on the interfacial friction factor. Experimental observations performed in the countercurrent configuration at constant liquid flow rate show that if the superficial gas velocity is raised it induces an increase in both the film thickness and, consequently, of the interfacial friction factor. By contrast, working cocurrently at constant liquid flow rate, if the gas flow rate is increased, a decrease in film thickness is induced. In this work, for the cocurrent configuration, a conservative assumption of neglecting the third term of Eq. 35 is introduced. This implies assuming the maximum value of the film thickness and consequently the maximum value of the interfacial friction factor.

Finally, to solve the model we need to know the dynamic liquid holdup, h_l, to define the constants B1, B2, B3, B4, and α (available in Table 1 for the most commonly used packings), and to perform an iterative procedure to evaluate shear stress and film thickness.

Experimental Results and Discussion

In this work, Mellapak and BX structured packings were studied. These types of packings differ from one another in some geometric properties (corrugation angle, specific surface area, void fraction) and in the material they are made of: plastic or metal sheet for the Mellapak type, plastic or metal gauze for the BX type. Experimental pressure drop and liquid holdup data were obtained in pilot columns, both in countercurrent and cocurrent gas–liquid flows. Moreover, experimental data published in the literature were considered.

Dry pressure drop

In the present work, experimental data for dry pressure drops on a column equipped with Mellapak 250Y metal sheet packing (100 mm inner diameter and 2 m packing height) were obtained. Analysis of the experimental pressure drops allowed computation of the two constants, B1 and B2, necessary for evaluation of the gas friction factor. The friction factor computed in this way has been corrected, taking Eq. 18 into account, for the prediction of the gas friction factor in Mellapak packings with different specific surface areas. This is an important improvement over the other published models, which are obliged to define different adjustable parameters for each type of packing. This approach makes it possible to accurately compute dry pressure drops in packings with different specific surfaces, as shown in Figure 3, where some experimental data generated by Spiegel and Meier (1992) are compared with the results obtained with the present model. Constants B1 and B2 have also been valuated for other packings (see Table 1), basing the analysis on experimental data performed in the present work and on data reported by the manufacturers.

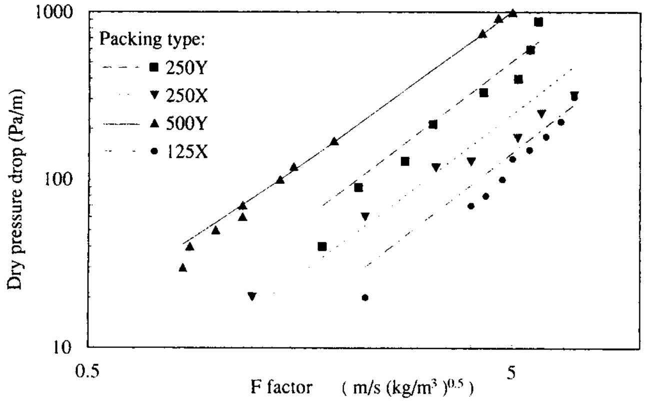

Figure 3. Dry pressure drop vs. *F* factor.

Comparison between experimental and computed data. (Mellapak-type packings; column diameter 1 m; experimental data by Spiegel and Meier (1992).)

The present model can be used to predict pressure drops in structured packings made both of sheets, such as the Mellapak type (see Figure 3), and of gauzes, such as the BX type (see Figure 4). The latter figure shows that a good prediction of experimental data is obtained both by the present model and the model suggested by Stichlmair et al. (1989), whereas the model of Rocha et al. (1993) tends to underestimate the experimental data; the same results have also been obtained if experimental data performed by the manufacturer (Sulzer, 1991) are analyzed.

Irrigated pressure drop and flooding

In the present work some new experimental data on irrigated pressure drops were obtained both with Mellapak 250Y

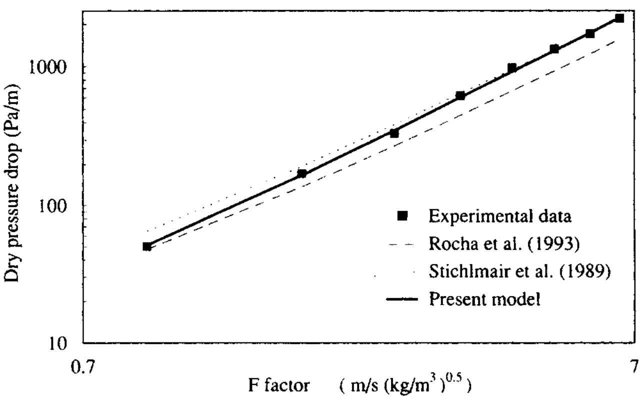

Figure 4. Dry pressure drop vs. *F* factor.

Comparison between experimental and computed data. (BX metal; column diameter 50 mm; experimental data obtained in this work.)

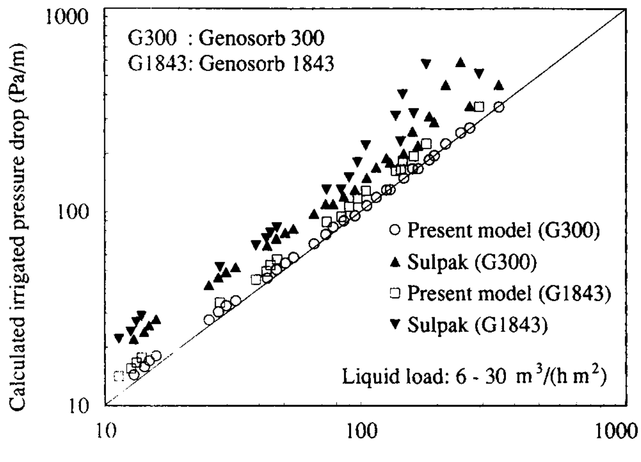

Figure 5. Irrigated pressure drop.

Comparison between experimental and computed data. (Mellapak 250Y metal; column diameter 100 mm; air–Genosorb systems; countercurrent flow experimental data obtained in this work.)

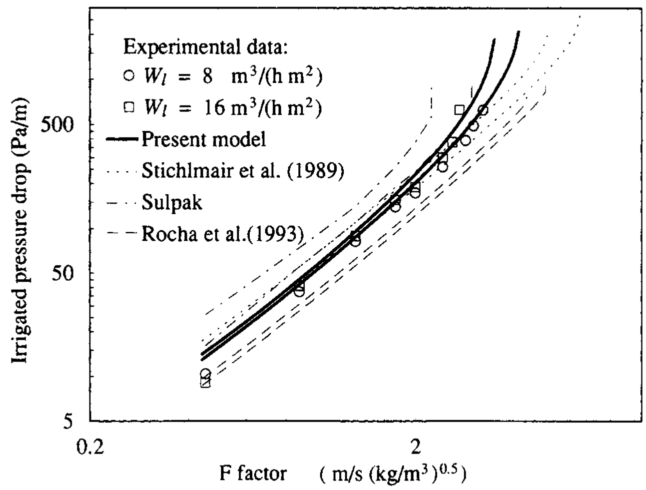

Figure 6. Irrigated pressure drop vs. *F* factor.

Comparison between experimental and computed data. (Mellapak 250Y metal; column diameter 100 mm; air-water system; countercurrent flow experimental data obtained in this work.)

and with BX metal gauze packings. One of the goals of the work is to respond to the lack of experimental pressure drop data in columns working with liquid phases other than water. For this reason, besides water, two high-boiling commercial liquids were considered: Genosorb 300, a mixture of polyethylene glycol dimethylethers, having a viscosity of about 7.7 cP and a surface tension of 38 dyne/cm, and Genosorb 1843, a mixture of polyethylene glycol dibutylethers, characterized by a viscosity of about 5 cP and a surface tension of 34 dyne/cm.

Another goal of the present work is to generate some data for columns working cocurrently, because, despite several related advantages, no data have ever been published for this configuration. The new data obtained with systems different from air–water are reported in Figure 5. This figure shows a parity plot for irrigated pressure drop made with the two different types of liquids in a column working countercurrently and equipped with Mellapak 250Y packing for liquid loads ranging from 6 to 30 $m^3/(h \cdot m^2)$. The comparison between experimental and computed data has been limited to the present model and to the results obtained with Sulpak, that is, a special software package used to design columns equipped with structured packings. This choice was compulsory because the model proposed by Stichlmair et al. (1989) has been tested only on air–water systems, while the model proposed by Rocha et al. (1993), applied by the authors to distillation service as well, uses the liquid holdup as a fundamental parameter, but for the liquid holdup gives a relation tested only with air–water systems. Note that the present model predicts the experimental data with good accuracy (mean square errors of about 20%), while Sulpak systematically tends to overestimate the experimental values.

The present model can also be used to predict pressure drop in columns working with air–water systems, and in this case the results can be compared with the results obtained by applying other published models. Figure 6 shows experimental data obtained in this work using air and water as working fluids, with liquid loads ranging from 8 to 16 $m^3/(h \cdot m^2)$. The tested column has an inner diameter of 0.1 m and is equipped with metal Mellapak 250Y structured packing. Comparison is made between the present model, the model suggested by Stichlmair et al. (1989), that of Rocha et al. (1993), and the results obtained using Sulpak. Also in this case the proposed model enables estimation of the experimental data with good accuracy, whereas the other models introduce systematic errors. In particular, these experimental results show that the Sulpak package tends to overestimate the experimental pressure drop data, while the models suggested by Stichlmair et al. (1989) and Rocha et al. (1993) overestimate the maximum capacity of the column.

The experimental data obtained in the present work have been plotted in the preceding figures, and it has been shown that the proposed model allows good prediction of the experimental data. This behavior has been confirmed by analyzing experimental data generated in different laboratories with columns of different diameters. In particular, Figure 7 com-

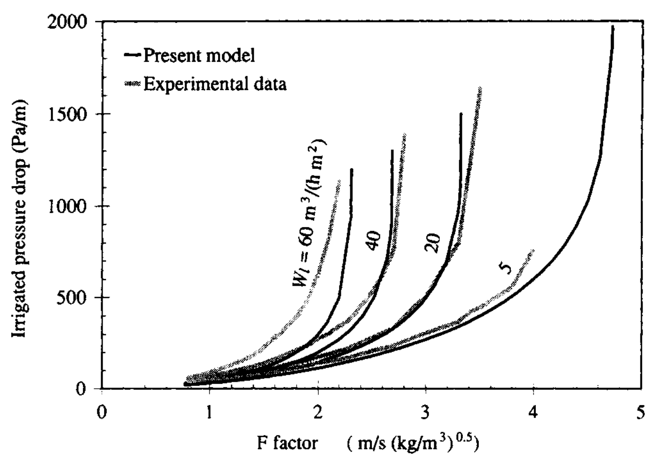

Figure 7. Irrigated pressure drop vs. *F* factor.

Comparison between experimental and computed data. (Mellapak 250Y metal; column diameter 300 mm; air-water system; countercurrent flow experimental data by Meier et al. (1979).)

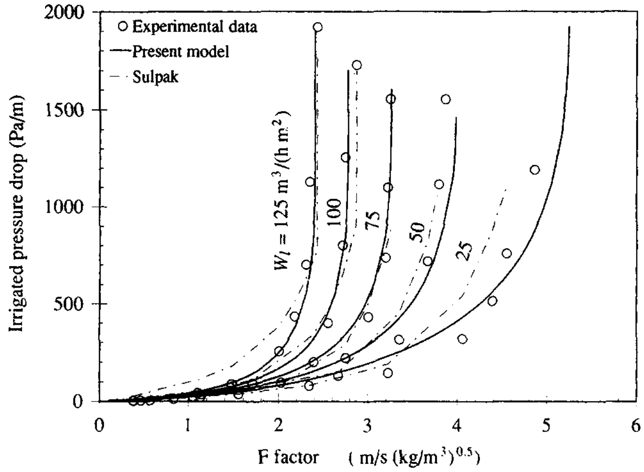

Figure 8. Irrigated pressure drop vs. *F* factor.

Comparison between experimental and computed data. (Mellapak 250X metal; column diameter 1 m; air-water system; countercurrent flow experimental data by Suess and Spiegel (1992).)

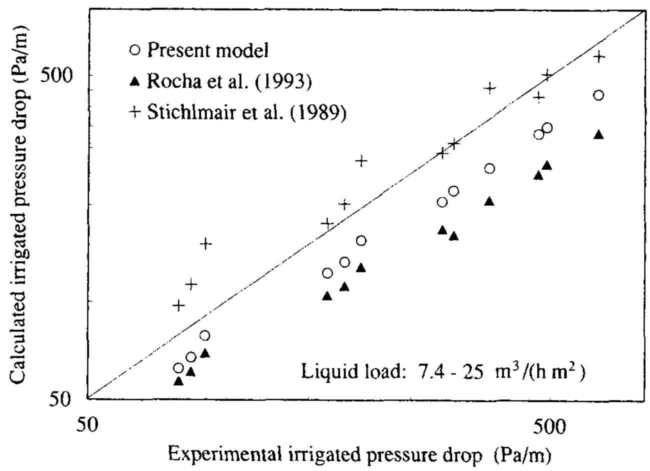

Figure 9. Irrigated pressure drop.

Comparison between experimental and computed data. (BX metal; column diameter 50 mm; air-water system; countercurrent flow experimental data obtained in this work.)

pares computed and experimental data performed by Meier et al. (1979) in a test column with a diameter of 0.3 m, with liquid load ranging from 5 to 60 $m^3/(h \cdot m^2)$, and shows a good prediction of the experimental data. Same good results can also be obtained if experimental data performed by manufacturers in columns equipped with plastic Mellapak 250Y (Sulzer, 1991) are analyzed.

The experimental results have shown that the present model enables good prediction of pressure drops in columns equipped with Mellapak Y structured packings. It will now be shown how the same model can also be used to predict pressure drops in columns equipped with different structured packings. Figure 8 shows a comparison between experimental and computed values relating to a column equipped with Mellapak 250X for liquid loads varying from 25 to 125 $m^3/(h \cdot m^2)$. This packing differs from the previous type of Mellapak by the corrugation angle. The figure shows that in this case the present model can also be used to predict the pressure drop and the flooding conditions while maintaining high accuracy. The comparison has been limited to the present model and the Sulpak model because both Stichlmair's and Rocha's models can be applied only to columns equipped with the Mellapak 250Y packing.

As for the dry case, the same experimental analysis can be applied not only to metal/plastic sheet packing but also to gauze packing. Figure 9 shows a parity plot of pressure drops where the experimental data were generated in this work and were obtained in a column equipped with BX metal structured packing [inner diameter 50 mm, liquid load ranging from 7.4 to 25 $m^3/(h \cdot m^2)$]. This figure compares the present model and the models suggested by Rocha et al. (1993) and Stichlmair et al. (1989). It can be seen that the model suggested by Rocha et al. (1993) greatly underpredicts the experimental values of pressure drop, the present model slightly underpredicts the same data, and the model suggested by Stichlmair et al. (1989) presents a good fit of the experimental data. The situation changes if a larger column is analyzed. Figure 10 shows the experimental data obtained in a column with an inner diameter of 508 mm, and experimental data were fitted by the empirical equations suggested by Robbins (1991). In this case the model suggested by Stichlmair et al. (1989) tends to overestimate the experimental data, while the model suggested in this work and the model proposed by Rocha et al. (1993) give a good data prediction.

Analysis of Figures 9 and 10 shows that the models suggested by Rocha et al. (1993) and Stichlmair et al. (1989) are not able to predict the influence of the column diameter. The model proposed by Rocha et al. (1993) tends to underestimate pressure drops in small columns, while the model suggested by Stichlmair et al. (1989) tends to overestimate pressure drops in large columns. Figures 9 and 10 also show that the present model is able to account for the effect of column diameter if a gauze metal packing is used. Moreover, good predictions have also been obtained analyzing experimental data performed by the manufacturer (Sulzer, 1991) with packings made with plastic materials.

Finally, a comparison can be made between the available

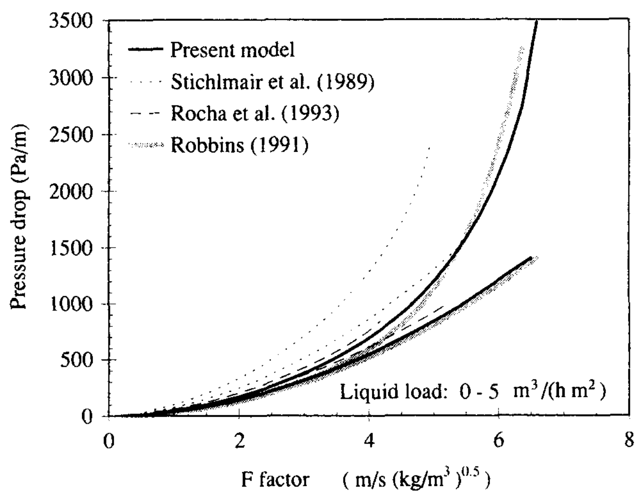

Figure 10. Pressure drop.

Comparison between experimental and computed data. (BX metal; column diameter 508 mm; air-water system; countercurrent flow experimental data obtained by Koch and interpolated by Robbins (1991).)

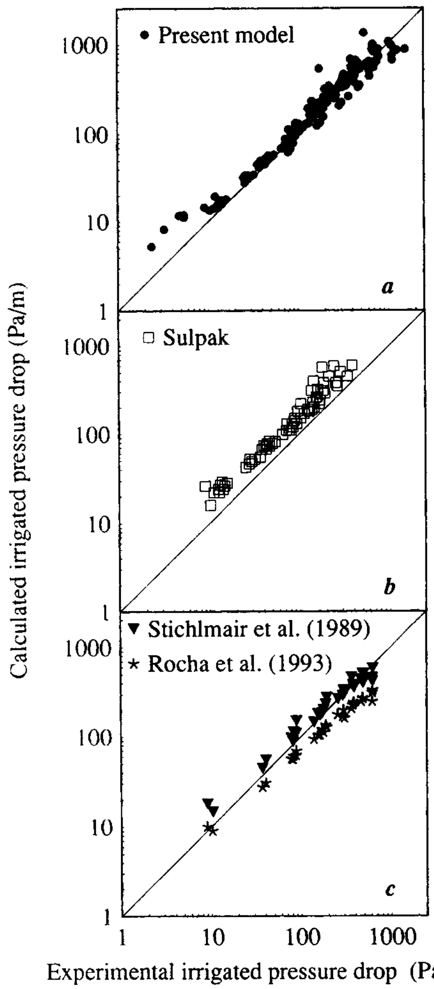

Figure 11. Irrigated pressure drop (countercurrent flow).

Comparison of experimental measurements with: (*a*) present model; (*b*) results of Sulpak package; (*c*) models proposed by Rocha et al. (1993) and Stichlmair et al. (1989).

models, with changing liquid physical properties, structured packing, and column diameter. Figure 11 shows a parity plot of pressure drops: in Figure 11a the calculated values are obtained by applying the proposed model; the experimental values refer to various gas–liquid systems, column diameters, and packing types. Figure 11b compares experimental pressure drop data with results obtained by applying the Sulpak package, showing systematic overprediction of the experimental value. Finally, in Figure 11c, the computed values are obtained by applying the models suggested by Rocha et al. (1993) and Stichlmair et al. (1989) (only experimental data regarding air–water systems and the Mellapak 250Y and BX packing types were considered). It will be noted that the model suggested by Rocha et al. (1993) systematically tends to underestimate, whereas good agreement is shown between predicted and experimental values with the model of Stichlmair (1989). However, the following limitations of these two models must be remembered: the adjustable parameters are given only for air–water systems, no diameter effect is taken into account, and the models can be applied only to BX and Mellapak 250Y packings.

As pointed out by Billet (1989), no generally useful theory has yet been developed to correctly predict the flooding point in absorption columns. The industrial design of the columns is left to the use of semiempirical diagrams based on evaluation of the flow factor $U_{sl}/U_{sg}\cdot(\rho_l/\rho_g)^{0.5}$ as suggested by Sherwood and Pigford (1952). There is no doubt that this method is suitable only for rough estimations whereas the present model makes it possible to compute the flooding conditions by taking into account the flow rates and physical properties of the working fluids. Figure 12 shows comparisons between various experimental data and the semiempirical relations available in the literature.

No model can be found in the literature that makes it possible to compute pressure drops in columns working cocurrently, and no experimental data obtained for this configuration are found, despite the advantages (high gas loadings and smaller equipment with low pressure drops) derived from applying the cocurrent configuration in some particular cases, such as the abatement of some acid gases with caustic solutions. The model presented in this article can be easily implemented for this configuration as well. Figure 13 shows the experimental and computed data vs. *F* factor for a column equipped with BX structured packing using air and water as

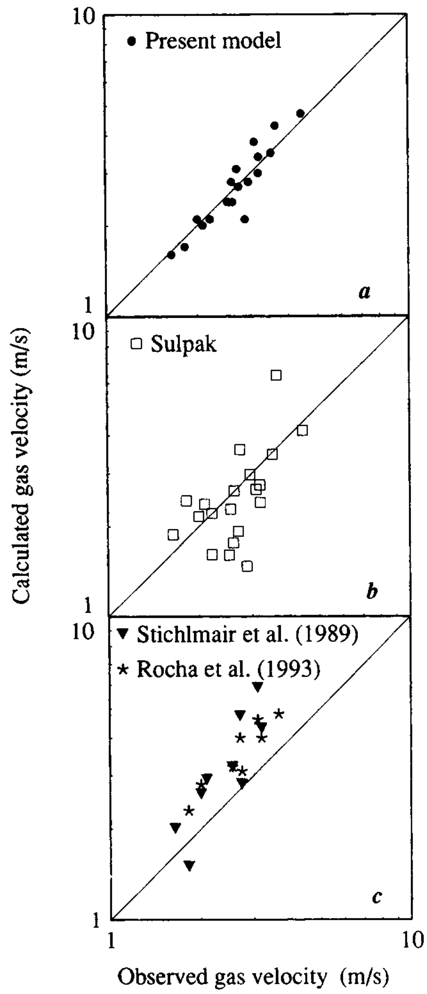

Figure 12. Gas velocity at flooding point.

Comparison between experimental and computed data obtained by using: (*a*) present model; (*b*) results of Sulpak package; (*c*) models proposed by Rocha et al. (1993) and Stichlmair et al. (1989).

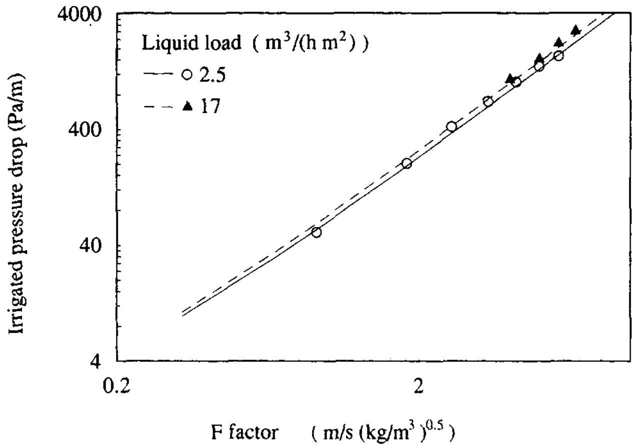

Figure 13. Irrigated pressure drop vs. *F* factor.

Comparison between experimental and computed data. (BX metal; column diameter 50 mm; air–water system; cocurrent flow experimental data performed in this work.)

working fluids, whereas Figure 14 shows the comparison between computed and experimental data by changing the structured packings, BX and Mellapak 250Y, and working fluids. As can be observed from these figures, the proposed model also gives an acceptable overall fit to the experimental values for columns working cocurrently.

Liquid holdup

The suggested model allows, with an iterative procedure, the evaluation of the dependence of film thickness on liquid and gas flow rates. Since the wetted surface is a function of liquid load and does not depend on the gas flow rate over a large range of values of this parameter, it is possible, from Eqs. 31 and 19, to evaluate the behavior of the liquid holdup with changing gas and liquid loads. Figure 15 shows a comparison between computed and experimental data with two different systems, air–Genosorb 300 (Figure 15a) and air–water (Figure 15b), respectively. We can see that the present model is able to evaluate the dependence of liquid

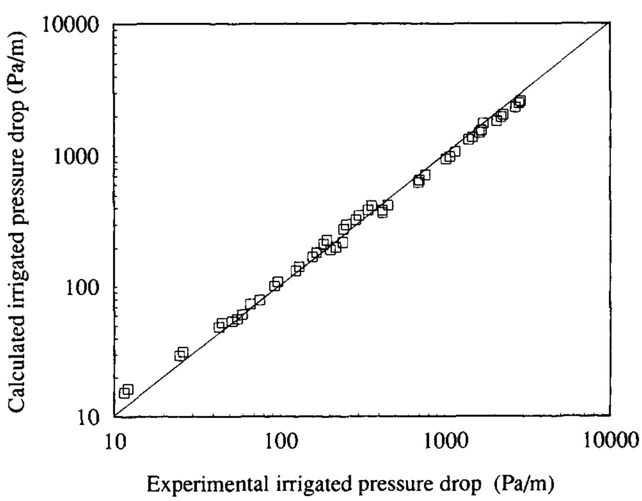

Figure 14. Irrigated pressure drop (cocurrent flow); comparison between experimental measurements and the present model.

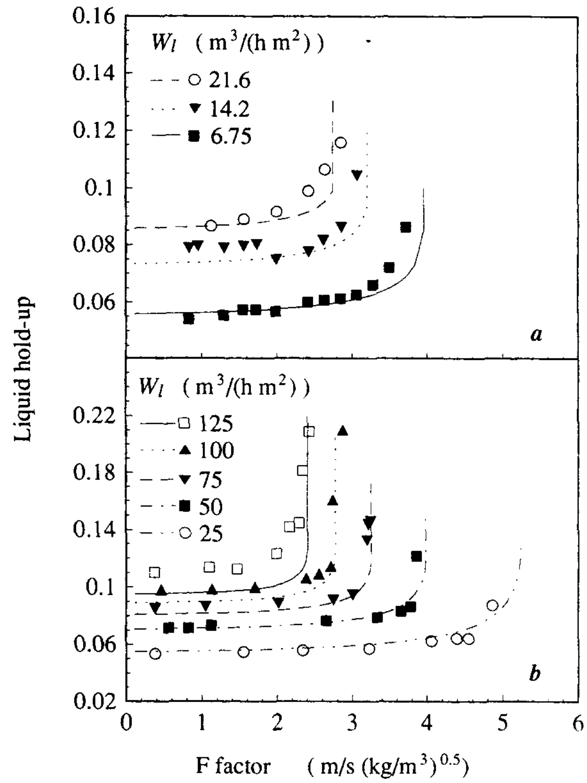

Figure 15. Liquid holdup vs. *F* factor.

Comparison between experimental and computed data. (*a*) Mellapak 250Y metal; column diameter 100 mm; air–Genosorb 300 system; countercurrent flow experimental data obtained in this work. (*b*) Mellapak 250X metal; column diameter 1 m; air–water system; countercurrent flow experimental data obtained by Suess and Spiegel (1992).

holdup on the *F* factor with changing Mellapak packing, liquid physical properties, and column diameters. It must be stressed that the present model can predict both experimental data performed in the present work and experimental data available in the literature.

As shown for the pressure drop, it is also possible to apply the model to predict the experimental trend of the liquid holdup in columns working cocurrently. Figure 16 shows a comparison between experimental and computed trends of liquid holdup vs. *F* factor for two different types of packing, Mellapak 250Y (Figure 16a) and BX (Figure 16b), in columns with different diameters. The proposed model allows good prediction of the experimental trend in both cases.

Conclusion

In this work a mechanistic model based on mass- and momentum-conservation equations has been developed to predict pressure drops and liquid holdup in columns working both countercurrently and cocurrently and equipped with packings of the structured type. The predictive accuracy of the proposed model has been tested by considering not only the experimental data obtained during this study but also experimental data reported in the literature. Experimental data on systems other than air–water were also obtained, together with previously unpublished data for cocurrent gas–liquid flow.

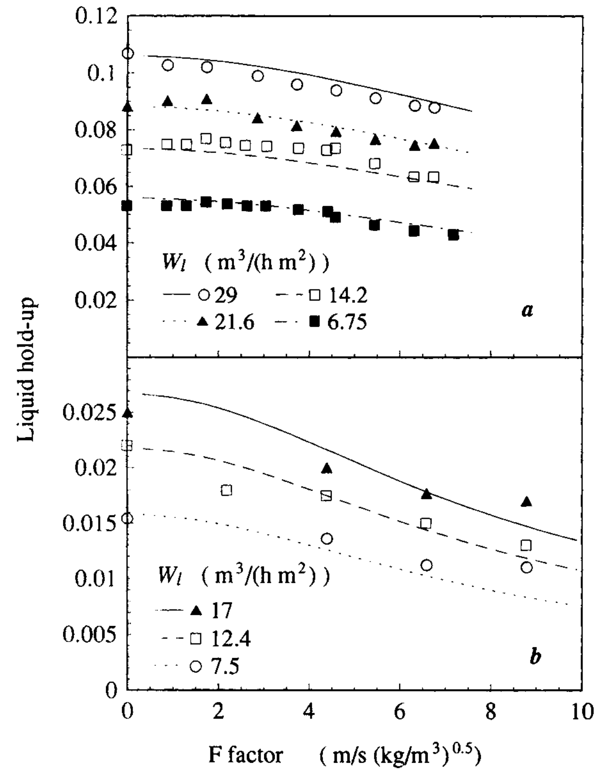

Figure 16. Liquid holdup vs. *F* factor.

Comparison between experimental and computed data. (*a*) Mellapak 250Y metal; column diameter 100 mm; air–Genosorb 300 system; cocurrent flow experimental data obtained in this work. (*b*) BX metal; column diameter 50 mm; air–water system; cocurrent flow experimental data obtained in this work.

The new model is based on a very fundamental approach and because of its nature can be used in all the operating regions encountered, from dry gas flow to flooding point, and can be easily extended to different types of structured packing.

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Notation

d_e = equivalent diameter
$F = U_{sg}(\rho_g)^{0.5}$, gas-capacity factor
g = gravitational constant
H_{og} = height of a gas-phase transfer unit
P = pressure
W = volumetric flow rate per unit cross-sectional area
x = axial coordinate
y = coordinate in a plane normal to z and oriented as liquid flow
z = coordinate normal to channel wall
δ = liquid film thickness
δ_0 = liquid film thickness measured in the absence of gas flow
μ = viscosity
$\mu_{l,0}$ = viscosity of water at 20°C
π = 3.14159...
ρ = density
σ = surface tension of liquid

Subscript and superscript

chan = channel
fl = flooding
l = liquid phase
TOT = overall

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