Distillation Columns Containing Structured Packings: A Comprehensive Model for Their Performance. 1. Hydraulic Models

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A mechanistically-based model has been developed to aid the analysis and design of distillation columns containing structured packings of the corrugated plate type. The model encompasses the important, and related, parameters of liquid holdup, pressure drop, flooding, and mass-transfer efficiency. Since it deals with the countercurrent contacting of liquid with gas or vapor, the model may also be applied to absorption or stripping processes. The model is developed from a consideration of the interaction of falling liquid films with upflowing vapors and thus takes into account the flow and physical property characteristics of the systems as well as geometric variables such as corrugation angle and surface enhancement. In this paper (part 1) the model is developed and applied to several sets of liquid holdup and pressure drop experimental data, including new data provided by the authors. The second paper in the series will deal with mass-transfer characteristics, with the model being shown to be dependent on the hydraulic aspects described in part 1. The information provided in these papers should have direct application to new designs, retrofits, or optimization of existing equipment.

Models describing the performance of packed columns that use corrugated packings of the regular type have been developed and implemented with a measure of success. The main variables of interest in such models are pressure drop, maximum flow capacity, and mass-transfer efficiency. A number of pressure drop models have been proposed (Bravo et al., 1986; Billet and Mackowiak, 1984; Stichlmair et al., 1989; Robbins, 1991); these have been discussed in part by Fair and Bravo (1990). The prediction of maximum capacity for structured packings has been constrained to the use of empirical correlations such as the one suggested by Fair and Bravo (1987) or to cumbersome methods such as that of Stichlmair et al. (1989). With respect to efficiency, the models of Bravo et al. (1985) and of Spiegel and Meier (1987) have been used with acceptable results.

These various correlations have been developed independently, but a common variable exists that should link all three issues: liquid holdup. Accurate prediction of holdup should permit development of more rigorous and thus more general models for structured packings. This series of papers is based on a sensible prediction of liquid holdup over the complete range of operating conditions, in turn to enable more accurate predictions of pressure drop, capacity, and mass-transfer efficiency.

This series of papers is divided into two main parts. The first (part 1) deals with general equations that lead to improved methods for predicting liquid holdup, pressure drop, and flooding in columns containing structured packings. The second part (part 2) provides an improved model for mass transfer that is consistent with the hydraulic parameters introduced in Part 1.

General Definitions

The relationships presented here are valid for structured packings of a corrugated nature and are based on the general approach of considering the flow channels within the packing as a series of wetted wall columns with a geometry that depends on the angle and size of the corrugations. This approach was first described by the present authors in 1985 and later modified by the same authors (Bravo et al. 1985, 1986).

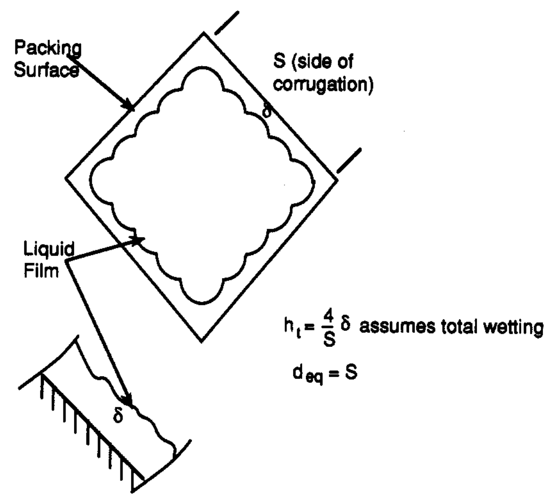

Figure 1. Cross section of flow channel, structured packing.

In the present development, the wetted wall flow channel is considered to have a diamond-shaped cross section as indicated in Figure 1. The diamond is exactly equivalent to a triangle without a base, and the equivalent diameter for this geometry is the side of the triangle S, which is also the side of the corrugation.

Effective Phase Velocities. Effective velocities of the gas and liquid are defined by

$$U_{ge} = \frac{U_{gS}}{\epsilon(1 - h_t)\sin\theta} \tag{1}$$

$$U_{Le} = \frac{U_{LS}}{\epsilon h_t \sin\theta} \tag{2}$$

It will be noted that a correction for the space occupied by liquid has been added to previously-used definitions. A relative velocity of gas to liquid would then be defined as

$$U_r = U_{Le} + U_{ge} \tag{3}$$

Effective Gravity. The force acting on the liquid to move it downward through the packing is gravity. Several

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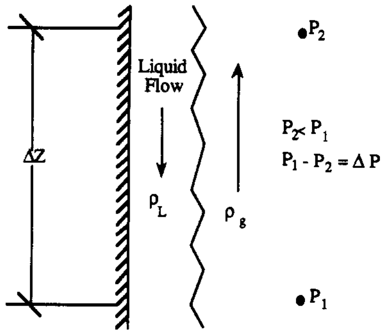

Figure 2. Liquid film flow down the surface of a structured packing element.

forces oppose gravity: (a) liquid buoyancy (important at high pressures); (b) vapor pressure drop; (c) drag on the liquid film by the vapor. The flow of liquid can be considered analogous to liquid flow in a wetted wall column, as shown in Figure 2. A force balance on the liquid film as it flows down the surface of the packing can be expressed as

net downward head = gravity head − buoyancy head − gas pressure difference − surface drag head

or

$$\rho_L \Delta Z g_{eff} = \rho_L \Delta Z g - \rho_g \Delta Z g - \Delta P - Q\Delta P \tag{4}$$

where Q is a constant relating pressure drop (or gas velocity) to surface drag, and g_{eff} is effective gravity as discounted by the forces opposing it. This balance neglects the effects of drag of the liquid on the solid surface. Rearrangement of the force balance yields the following definition for an "effective gravity":

$$g_{eff} = g\left[1 - \frac{\rho_g}{\rho_L} - K_1\left(\frac{\Delta P}{\Delta Z}\frac{1}{\rho_L g}\right)\right] \tag{5}$$

The last term in the expression lumps together the effects of pressure drop and surface drag, and includes the assumption that the value of K_1 depends only on the packing type. The value of effective gravity clearly would tend to decrease markedly at high pressures (high vapor densities) and at high loadings because of high pressure drop and drag. In the limit, flooding occurs at $g_{eff} = 0$. Accordingly,

$$K_1 = \frac{(\rho_L - \rho_g)g}{(\Delta P/\Delta Z)_{flood}} \tag{6}$$

K_1 is expected to be a constant for a particular shape of packing regardless of size or surface characteristics. It is well-known that systems that exhibit low phase density differences also flood at lower pressure drop conditions; the form of eq 6 appears able to handle this fact.

A combination of eqs 5 and 6 provides

$$g_{eff} = g\left[\left(\frac{\rho_L - \rho_g}{\rho_L}\right)\left(1 - \frac{\Delta P/\Delta Z}{(\Delta P/\Delta Z)_{flood}}\right)\right] \tag{7}$$

Liquid Holdup

The assumption is made that liquid flows on the surface of the packing as a film. If the entire surface is covered and no suspended liquid exists, then holdup can be described in terms of the thickness of the film by

$$h_t = 4(\delta/S) \tag{8}$$

where h_t is total holdup, which comprises static and operating components:

$$h_t = h_{stat} + h_{op} = \frac{4F_s'\delta_{stat}}{S} + \frac{4F_o\delta_{op}}{S} \tag{9}$$

The term F_s' is a correction factor that accounts for all the surface not being wet when only static holdup occurs, and F_o represents the corresponding correction when liquid flow is present.

Static holdup is the only contribution to total holdup when liquid velocity is zero. For this situation Shi and Mersmann (1985) presented an expression for film thickness on a horizontal smooth plate as a function of physical properties. Their expression has been corrected for the angle of inclination of the corrugations and for the buoyancy effect of the gas density. These corrections (θ, ρ_g/ρ_L) are theoretically based, while the correction for surface roughness and capillarity, needed for F_s' in eq 9, must be empirical. The new expression for the thickness of the static holdup film is

$$\delta_{stat} = \left[2\sigma\frac{1 - \cos\gamma}{\rho_L g(1 - \rho_g/\rho_L)\sin\theta}\right]^{0.5} \tag{10}$$

where γ is the contact angle of the liquid with the solid surface.

The average film thickness during operation can be defined by a modification of the classical falling film equation (Bird et al., 1960) that incorporates the definitions of the effective liquid velocity (eq 2) and the effective gravity (eq 5):

$$\delta_{op} = \left[3\mu_L\frac{U_{LS}}{\rho_L \epsilon h_t g\left(1 - \frac{\rho_g}{\rho_L} - K_1\left(\frac{\Delta P}{\Delta Z}\right)\left(\frac{1}{\rho_L g}\right)\right)\sin\theta}\right]^{0.5} \tag{11}$$

Interfacial Area. As described above, the amount of surface area available in the system is directly related to liquid holdup, and in particular to operating holdup. The connection between interfacial area and holdup makes possible a relationship between mass-transfer efficiency and holdup. The inclusion of the term F_o in eq 9 gives a direct tie to mass-transfer efficiency, and several options are available for its calculation. Shi and Mersmann (1985) offer an expression for the interfacial area based on fluid hydraulics over an inclined plane:

$$\frac{a_e}{a_p} = 0.76(We_L Fr_L)^{0.15}\frac{A'd_{eq}^{B'}}{Re_L^{0.2}\epsilon^{0.6}(1 - 0.93\cos\gamma)(\sin\theta)^{0.3}} \tag{12}$$

where A' and B' depend on the packing material. Equation 12 does not include an effect on interfacial area of gas loading, liquid distribution, or heat effects.

Bravo and Fair (1982) developed expressions for the effective interfacial area of randomly-packed distillation and absorption/stripping columns, derived from mass-transfer studies. Their expressions take into account gas velocity, bed height, and heat effects. Structured packing interfacial areas, however, have been found to be relatively uninfluenced by gas rate and to be much more dependent on liquid rate (Fair and Bravo, 1987; Bravo et al., 1992). For developing a final holdup model, the expressions of Shi/Mersmann and Bravo/Fair were studied as alternatives, and the former was found to provide a somewhat better fit of available data.

Table I. Relative Static Holdups and Surface Correction Factors for Various Metal Structured Packings[a]

packing	relative holdup	surface correction factor, F_s	surface description
Glitsch Gempak 2AT	0.67	0.009	smooth surface, small holes
Flexipac 2	1.00	0.014	fluted surface, large holes
Glitsch Gempak 2A	1.04	0.015	lanced surface, large holes
Sulzer BX	2.45	0.018	gauze, large holes
Jaeger Maxpak	1.30	0.020	smooth surface, large notches
Norton Intalox 2T	1.89	0.029	grated surface, no holes

[a] Holdup data valid only for water.

Table II. Summary of Experimental Data and Model Fit (System: Air/Water at Atmospheric Pressure)

	source	
	McNulty and Hsieh (1982)	Chen, Kitterman, and Shieh (1982, 1983)
packing type (S, ϵ)	Flexipac 1 (0.009 m, 0.91) Flexipac 2 (0.018 m, 0.95) Flexipac 3 (0.036 m, 0.96) Flexipac 4 (0.072 m, 0.98)	Gempak 4A (0.009 m, 0.91) Gempak 3A (0.013 m, 0.93) Gempak 2A (0.018 m, 0.95) Gempak 1A (0.036 m, 0.96)
range of U_{LS} (m/s) (for holdup expts)	0.0068–0.340	0.0068–0.204
range of U_{gS} (m/s)	0.461–4.367	0.508–4.326
no. of joint holdup-press. drop points	195	65

Holdup Correlation. Equations 9–11 were used to develop a predictive correlation for liquid holdup. It was necessary that validating data include holdup, capacity, and pressure drop information for the same experimental runs. The data of McNulty and Hsieh (1982), for Flexipac, and of Chen et al. (1982, 1983), for Gempak, were found to satisfy this requirement.

It was first necessary to determine the value of K_1 from maximum capacity data using eq 6. The value selected for $(\Delta P/\Delta Z)_{\text{flood}}$ has a strong influence on the value of K_1. As indicated by Fair and Bravo (1990), flooding does not necessarily occur at the same pressure drop for all liquid loadings. Nevertheless, the data showed that in most cases incipient flooding, as detected by a very sharp rise in pressure drop with gas loading, was present at pressure drops in the 900–1200 Pa/m range. Smaller packings exhibited a somewhat higher value of flooding pressure drop than did larger packings. The value of the flooding pressure drop appeared to depend on the value of the flow parameter (FP) as well as on the size of the packing.

For the sake of simplicity and to maintain positive values of g_{eff} at all times, a value of 1025 Pa/m (1.25 in. H_2O/ft) was selected for the flooding pressure drop, in order to calculate K_1. Though not rigorously correct, this value allowed use of only one value of K_1 for all the packings analyzed and provided an adequate fit of the holdup data, as illustrated below. The value selected for a dimensionless K_1 is

$$K_1 = g\frac{\rho_L - \rho_g}{1025} \quad \text{(densities in kg/m}^3, g = 9.8 \text{ m/s}^2) \tag{13}$$

or

$$g_{\text{eff}} = g\left[\left(\frac{\rho_L - \rho_g}{\rho_L}\right)\left(1 - \frac{\Delta P/\Delta Z}{1025}\right)\right] \tag{5a}$$

These expressions are only valid for the air/water system and for the packings studied. In general, the value of K_1 to be used in other systems and for other packings may be obtained from eq 6. For structured packings, this pressure drop should lie between values of 900 and 1200 Pa/m.

The next step was to establish a model for static holdup. McNulty and Hsieh (1982) provided experimental holdup data for Flexipac 2. Equations 9 and 10 were fitted to their data with the following relationship:

$$h_{\text{stat}} = \frac{4}{S}F_s'\left[\frac{2\sigma(1 - \cos\gamma)}{\rho_L g(1 - \rho_g/\rho_L)\sin\theta}\right]^{0.5} \tag{14}$$

with $F_s' = 0.014$ for the data set.

It should be noted that the correlation constant $F_s' = 0.014$ is independent of the size of the packing and depends only on the nature of the surface. Its value for packing with a fluted and perforated surface indicates that about 1.4% of the packing surface is wet with water at no liquid load. Table I shows values of F_s' derived from relative static holdup data obtained by the authors, for several structured packings and the air/water system. Holdup data for Flexipac 2, taken by McNulty and Hsieh, were used as the reference. An increasing value of F_s implies increasing degree of surface treatment.

Once the expressions for the effective gravity and static holdup were well established, the Shi–Mersmann correlation for holdup was fitted to the data, using eqs 9 and 12. The best fit, which also preserves the interfacial area expression, is

$$F_o = 7.2453\left[\frac{0.76(We_L Fr_L)^{0.15}(5.64)S^{0.397}}{Re_L^{0.2}\epsilon^{0.6}(1 - 0.93\cos\gamma)(\sin\theta)^{0.3}}\right] \tag{15}$$

Equation 15 is based on the Shi–Mersmann relationship for interfacial area. A final expression for liquid holdup will include an interfacial area term that properly correlates the mass-transfer data.

The new holdup correlation may be summarized as

$$h_t = \left(\frac{4}{S}\right)F_s'\delta_{\text{stat}} + \left(\frac{4}{S}\right)F_o\delta_{\text{op}} \tag{16}$$

The value of F_s' can be obtained from Table I and the value δ_{stat} from eq 10. The value of F_o can be obtained from eq 15 and δ_{op} from eq 11.

Experimental Data and Model Fit. The results of using eq 16 to provide total holdup values as compared with data from the holdup data bank are shown in Figures 3 and 4 for several structured packings ranging in size from 6 to 25 mm (0.25 to 1.0 in.) crimp heights. As noted earlier, the data sets are for air/water and include pressure drop as well as holdup. These data are amply discussed in the original references and are the same ones used by Bravo et al. (1986) for the original development of their pressure drop equation for structured packings. The most important features of the data bank are summarized in Table II.

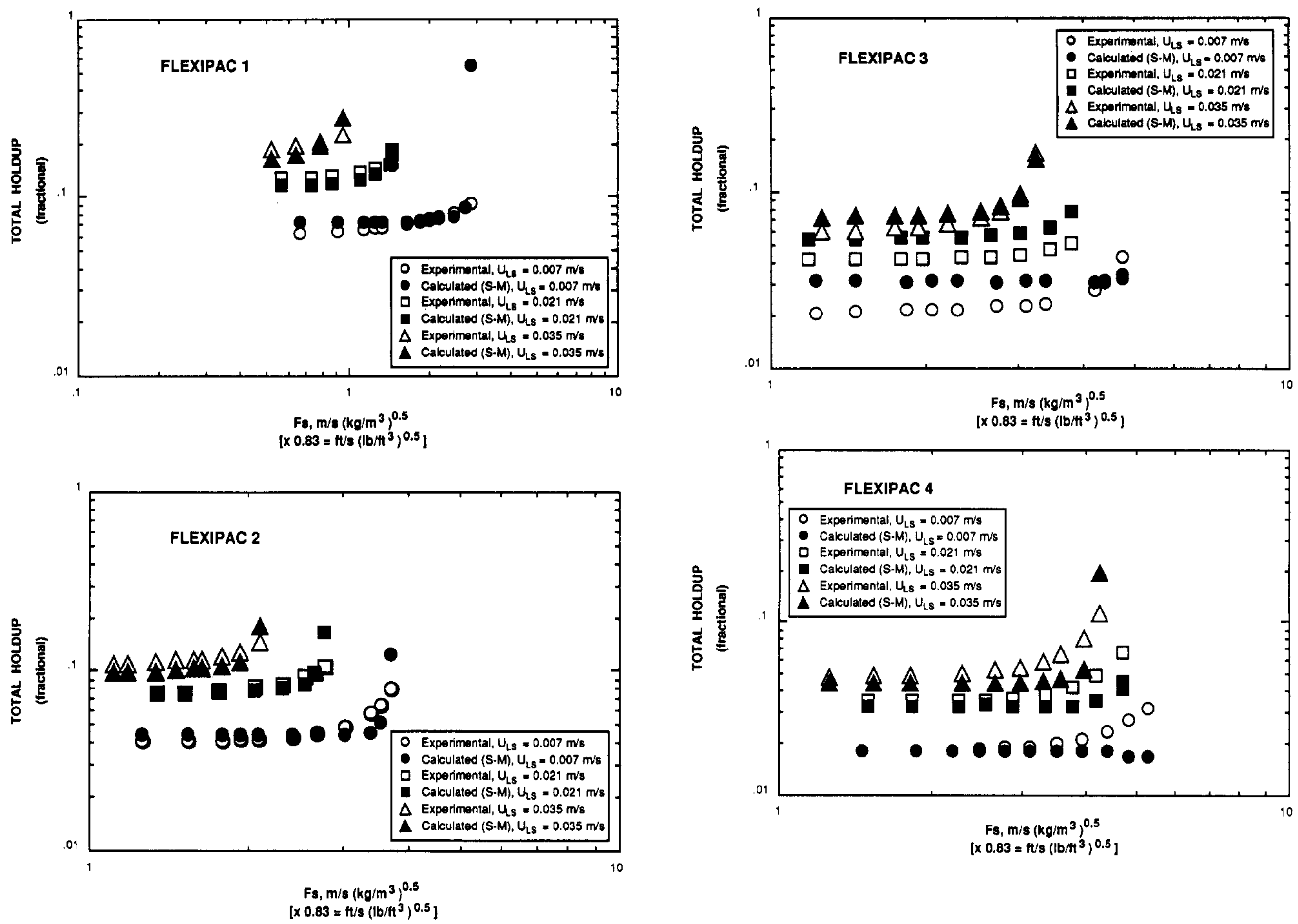

Figure 3. Comparison of measured and calculated values of liquid holdup for Flexipac structured packings. Equation 16 was used for the calculations, with F_o values from the Shi–Mersmann model. Air/water, atmospheric pressure.

The fit is quite good. Importantly, the form of the holdup model tracks the data in the loading region. This results mainly from the use of the effective gravity concept. It is entirely possible that the behavior of interfacial area with gas loading follows different exponents in structured packings as compared to random packings. Since the former essentially eliminates form drag, most of the interfacial area is present in the form of liquid films on the packing surface. In the case of random packings, a great deal of interfacial area is supplied by drops and rivulets that would tend to be more affected by gas rate than the films present in structured packings.

Limitations of the Model and Simplifications. As presented here, the holdup model is applicable to structured packings of the corrugated sheet geometry. Furthermore, a corresponding value of pressure drop is needed in the calculation of the effective gravity to be used in eq 5. This means that if a prediction of holdup is needed in the absence of experimental data, an accurate prediction of pressure drop is required. Numerous authors have discussed the effect of liquid holdup on pressure drop. A good review of the subject may be found in Stichlmair et al. (1989). The interdependence of holdup and pressure drop forces a complicated numerical simultaneous solution to the holdup and pressure drop models. The next main section of this paper addresses the development of a pressure drop model and serves to validate further the holdup correlation as it allows for good pressure drop predictions.

The contribution of static holdup to total holdup is usually very small and its calculation adds a certain complexity to the model. For approximate calculations, a simplification of eq 9 is possible

$$h_t = 4F_t(\delta_{op}/S) \tag{17}$$

where F_t is a correction factor for total holdup in terms of available interfacial area. Equation 17 is obviously not valid at zero liquid rate. As before, values of F_t based on the Shi/Mersmann correlation were obtained to fit the experimental data. The resulting expression is

$$F_{t,S\text{-}M} = \frac{29.12(We_L Fr_L)^{0.15} S^{0.359}}{Re_L^{0.2} \epsilon^{0.6} (1 - 0.93 \cos \gamma)(\sin \theta)^{0.3}} \tag{18}$$

Equation 17 was found to fit the data as well as the more rigorous eq 16. An additional advantage is that eq 17 is not an implicit function of holdup as is eq 16. Equation 17 may be combined with eq 11 to give

$$h_t = \left(4\frac{F_t}{S}\right)^{2/3} \left(\frac{3\mu_L U_{LS}}{\rho_L (\sin \theta) \epsilon g_{eff}}\right)^{1/3} \tag{19}$$

Equations 17–19 provide a simpler model that provides a satisfactory fit of the data.

The holdup model presented here has been derived from air/water data for two different perforated surfaces (fluted and lanced) and a variety of packing sizes. The model accounts for variations in size but has yet to be tested for different systems and distinctly different surfaces. The very good fit achieved by the use of the model must be extended to systems other than air/water if it is to be generally useful. How the proposed model predicts holdup for some distillation runs at total reflux is shown in Figure 5. The experiments were carried out in the 0.43-m column

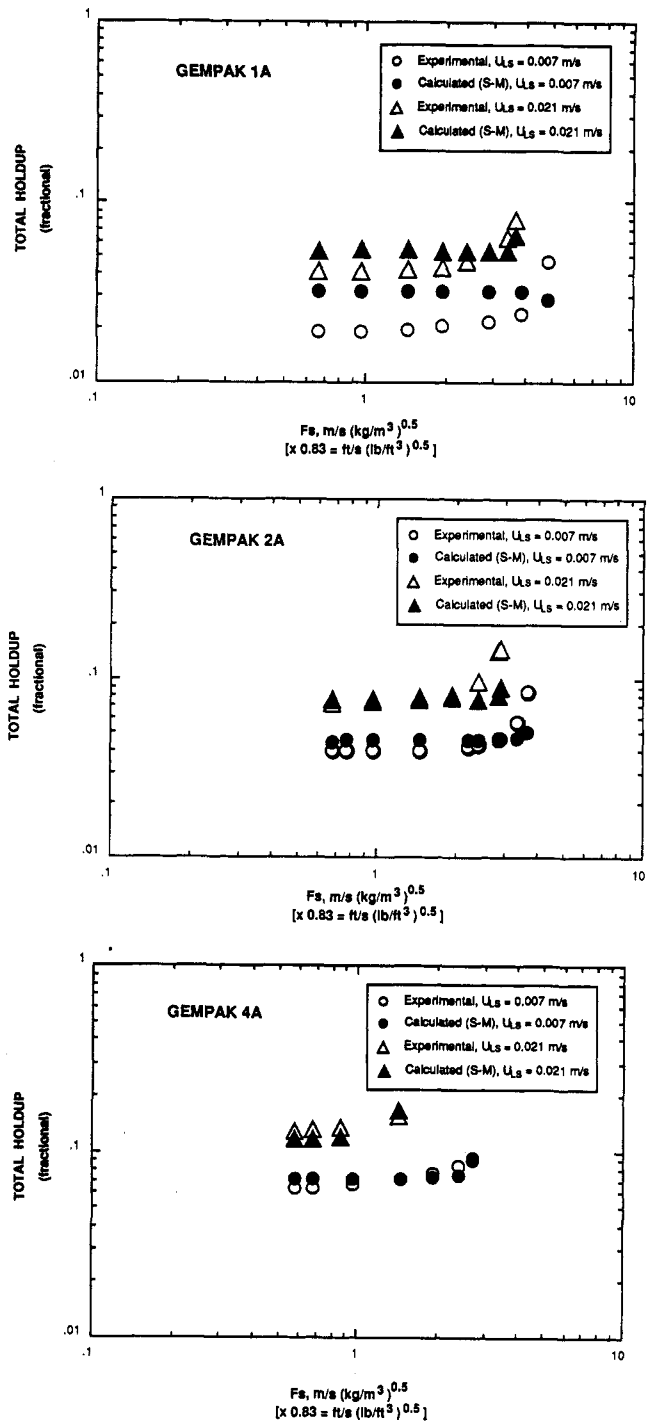

Figure 4. Comparison of measured and calculated values of liquid holdup for Gempak structured packings. Equation 16 was used for the calculations, with F_0 values from the Shi–Mersmann model. Air/water, atmospheric pressure.

at The University of Texas at Austin; the column and auxiliaries have been described by Fair and Bravo (1990). It should be noted that the model predicts a sharp increase in holdup at the experimentally-obtained flood point. Measured pressure drops were used in the determinations of holdup shown in the figure.

Pressure Drop and Flooding

As stated above, reliable prediction of holdup is crucial to the development of a pressure drop model that can be used in the loading region as well as below the loading point. This section describes the development of an improved pressure drop model and demonstrates its

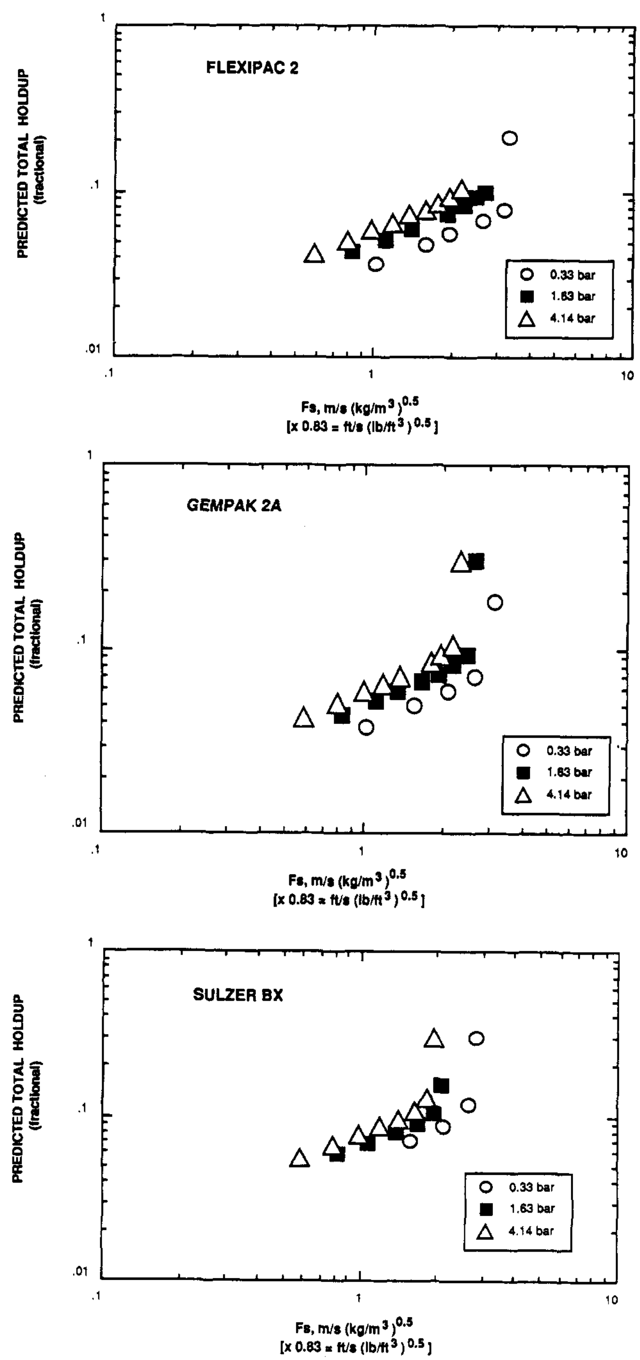

Figure 5. Predicted liquid holdup for the cyclohexane/n-heptane system at total reflux and the pressures indicated. Simplified model with eq 19 was used along with Shi–Mersmann parameters.

application to distillation experimental data as well as to air/water data.

Previous Work. Knowledge of the maximum hydraulic capacity and pressure drop of a packing are important because in many cases it provides a rational basis for design. Methods for the estimation of these parameters have been developed following one of three separate paths: (a) a generalized pressure drop correlation (GPDC) based on the original work of Sherwood et al. (1938) and Leva (1954); (b) empirical plots of capacity parameter vs flow parameter; (c) friction factor/dry pressure drop correction methods.

The first approach has been used for many years, and several updates and modifications have been made from time to time. The general-purpose diagram published by Eckert in 1970 is designed to provide both limiting capacity and pressure drop predictions. Packing type and size effects are forced to merge through the use of a packing factor that is presumed to be constant for each type and size.

Fair and Bravo (1990) discuss several methods for the prediction of the flood point and pressure drop in structured packings and emphasize the usefulness of empirical capacity plots. Such plots deal with specific packing types and sizes and suffer from not being generalized. Structured packing vendors use plots of this type to estimate capacity, but because of a limited data base are required to interpolate or extrapolate when unusual systems or flow conditions are encountered. In many cases significant anomalies have been found in the prediction of the maximum capacity of a structured packing when conditions such as high liquid loads and gas densities have required extrapolations of the plots.

A novel approach for the estimation of pressure drop and the flooding point for random as well as structured packings has been presented by Stichlmair et al. (1989). This approach is based on the determination of pressure loss in a dry bed of particles followed by a correction for the presence of liquid. The derivation of the model follows an analogy to a fluidized bed where the change in void fraction is caused by the presence of irrigating liquid. A very important feature of the approach is that it takes into account the direct effect of holdup on pressure drop, and vice versa. Prediction of holdup is key to the implementation of the model.

Another new method applicable to random as well as structured packings, albeit more empirical than the Stichlmair method, has been presented by Robbins (1991). This method has been validated with an extensive data bank that includes most of the commercially available random and a few of the structured packings. However, in many cases, the "data" used in the development of the correlation were obtained from vendor literature. The method appears to represent a significant refinement of the Eckert approach, but suffers in that required approximations or corrections depend on the system and operating range under consideration.

Still another new method applicable to random as well as structured packings is that of Kister and Gill (1991). These authors propose the use of the Sherwood–Leva–Eckert correlation and show how experimental pressure drop, flooding, and maximum operational capacity values compare with those predicted by the correlation. The authors also offer an equation for predicting the flood point; this equation is a function only of a packing factor, which makes it convenient for application.

A method specifically developed for the prediction of pressure drop in structured packings is that of Bravo et al. (1986). This method has proved to be reliable at low pressure drops, those typically found in structured packing applications, but not at conditions above the loading point, since it does not take liquid holdup into account.

Model Development. The model presented here, which is an extension of the model of Bravo et al., allows predictions within the loading region and provides significant insight into the determination of the maximum hydraulic capacity of a structured packing.

For gas flow through dry porous media, relationships between the friction factor and gas velocity have been discussed extensively in the literature. The more recent general models for pressure drop have included a correction for the dry pressure drop to account for the presence of liquid. Buchanan (1969), Bemer and Kalis (1978), Billet and Mackowiak (1984), and Bravo et al. (1986) all proposed the same general equation for the irrigated pressure drop based on a "channel" model:

$$\frac{\Delta P}{\Delta Z} = \frac{\Delta P_d}{\Delta Z}\left[\frac{1}{1 - K_2 h_L}\right]^5 \tag{20}$$

Stichlmair et al. (1989) proposed a slightly different form of eq 18 based on a particle model. Since the geometry of structured packings suggests that the channel model is more appropriate, eq 20 will be used as the basis for development of a new pressure drop correlation. This equation is fundamentally correct and can be derived theoretically with few assumptions. Buchanan (1969) and Bemer and Kalis (1978) have explained the development of the equation in detail.

The dry pressure drop is calculated using a conventional friction factor equation, as proposed by Bravo et al. in 1986:

$$\frac{\Delta P_d}{\Delta Z} = \frac{f \rho_g U_{ge}^{\ 2}}{S g_c} \tag{21}$$

where $U_{ge} = U_{gS}/\epsilon \sin \theta$.

The definitions of the effective gas velocity and equivalent diameter are consistent with those used in the holdup model development. Previous work involving the present authors showed that a single expression for the friction factor can be used for the range of geometries, surfaces, and flow conditions commonly encountered in structured packing applications (Stichlmair et al., 1989).

Dry Pressure Drop. Dry pressure drop data for two types of packings have been correlated to obtain friction factors. The data are the same as those used to develop the holdup correlation and are for the air/water system.

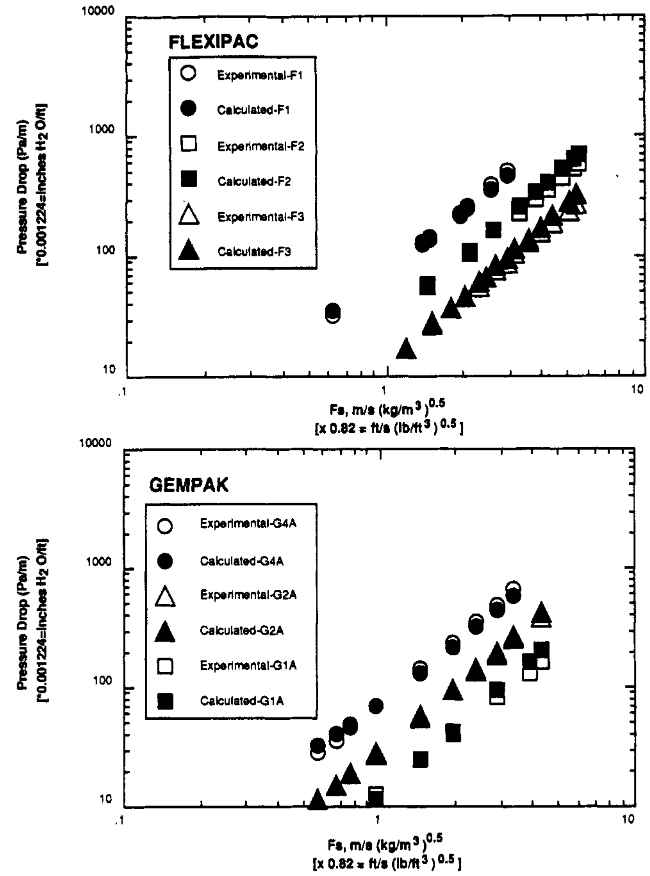

Figure 6. Comparison of measured and calculated values of dry pressure drop for structures packings. Air/water, atmospheric pressure. Equation 4 was used for the calculations. F1 = Flexipac; F2 = Flexipac 2; F3 = Flexipac 3; F4 = Flexipac 4; G1A = Gempak 1A; G2 = Gempak 2A; G4 = Gempak 4A.

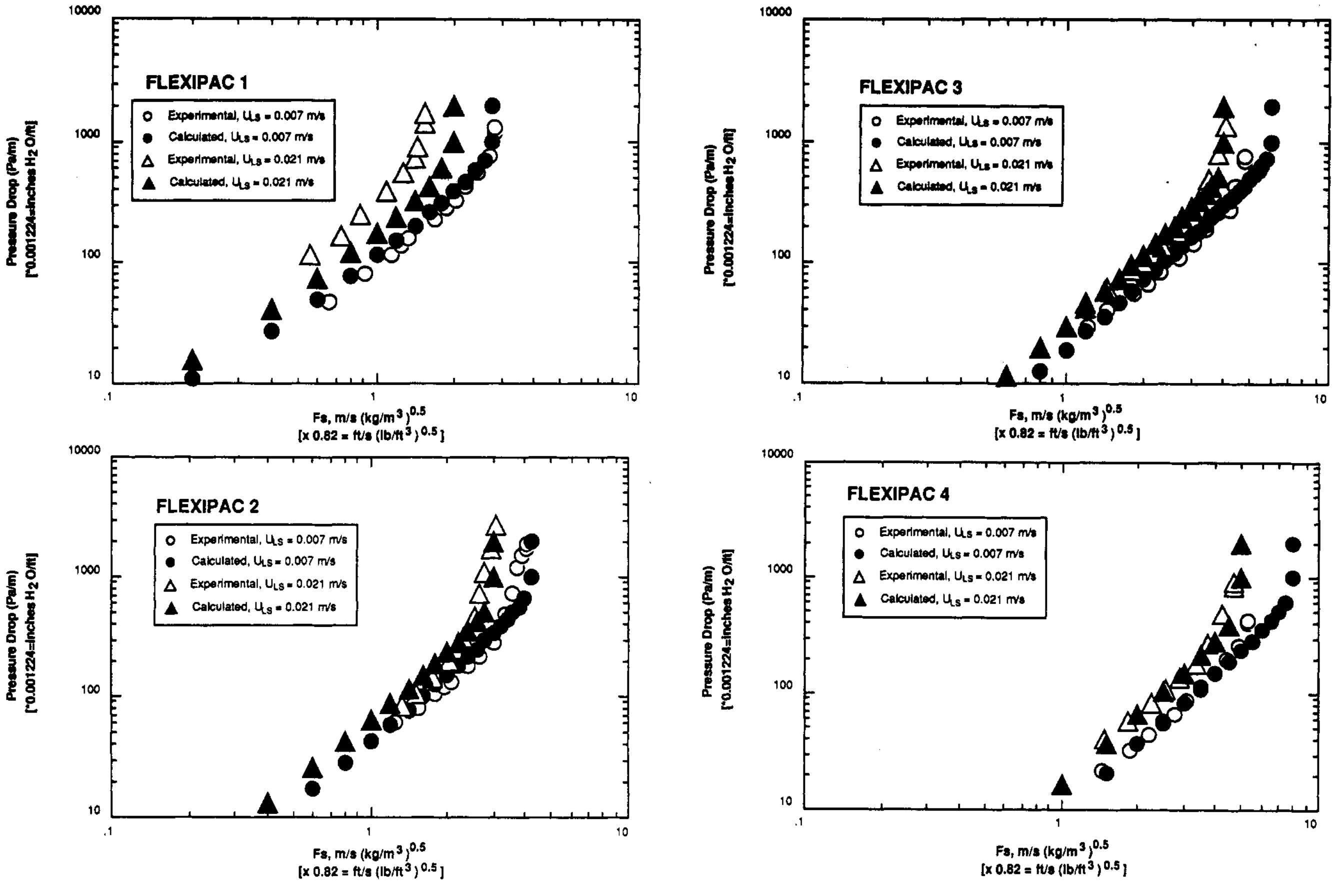

Figure 7. Comparison of measured and calculated values of irrigated pressure drop for Flexipac structured packings. Air/water, atmospheric pressure. Equations 20–29 were used for the calculations.

The correlating equation is

$$f = 0.177 + 88.774/Re_g \tag{22}$$

Combining eqs 21 and 22,

$$\frac{\Delta P_d}{\Delta Z} = \frac{0.177\rho_g}{S\epsilon^2(\sin\theta)^2}U_{gS}^2 + \frac{88.774\mu_g}{S^2\epsilon\sin\theta}U_{gS} = AU_{gS}^2 + BU_{gS} \tag{23}$$

where

$$A = \frac{0.177\rho_g}{S\epsilon^2(\sin\theta)^2} \tag{23a}$$

and

$$B = \frac{88.774\mu_g}{S^2\epsilon\sin\theta} \tag{23b}$$

The excellent fit of eq 23 to experimental data is shown in Figure 6. The data are for air/water and represent seven different packings.

Correlation Development—Irrigated Pressure Drop. The irrigated pressure drop, in accordance with eq 20, was correlated using an air/water data bank and for the same seven different structured packings represented in Figure 6. The expressions used for holdup and its development have been given earlier; the summary equations for holdup are

$$h_t = \left(4\frac{F_t}{S}\right)^{2/3}\left(\frac{3\mu_L U_{LS}}{\rho_L(\sin\theta)\epsilon g_{eff}}\right)^{1/3} \tag{24}$$

$$F_t = 29.12(WeFr)_L^{0.15}\frac{S^{0.359}}{Re_L^{0.2}\epsilon^{0.6}(1-0.93\cos\gamma)(\sin\theta)^{0.3}} \tag{25}$$

$$g_{eff} = g\left[\frac{\rho_L - \rho_g}{\rho_L}\right]\left[1 - \left(\frac{\Delta P/\Delta Z}{(\Delta P/\Delta Z)_{flood}}\right)\right] \tag{26}$$

where

$$\cos\gamma = 0.9 \quad \text{for} \quad \sigma < 0.055 \text{ N/m} \tag{27}$$

$$\cos\gamma = 5.211 \times 10^{-16.835\sigma} \quad \text{for} \quad \sigma > 0.055 \text{ N/m} \tag{28}$$

With the dry pressure drop and holdup equations established, correlating values for K_2 (eq 20) were obtained. It was noted that the values that gave the best fit to the air/water data had a linear dependence on packing size:

$$K_2 = 0.614 + 71.35S \quad (\text{with } S \text{ in meters}) \tag{29}$$

The fit of the pressure drop model (eqs 20–29) to experimental data for several packings under different loading and irrigation conditions is shown in Figures 7 and 8. It can be seen that the inclusion of the holdup correlation allows the predicted curves to follow the experimental data in the loading region and toward the flood point. This then indicates that the pressure drop model can be used for predicting liquid holdup. The use of predicted pressure drop values for this purpose has been studied, and the agreement with measured values is excellent. A representative application of calculated pressure drop to holdup prediction is shown in Figure 9.

Calculation Methods. Equations 20–29 form a system of nonlinear equations, with unknowns h_L and $\Delta P/\Delta Z$, that must be solved. A trial-and-error approach or a direct substitution algorithm is satisfactory for both analytical and computer purposes. Another solution approach is to substitute eqs 23–29 into eq 20. This leads to

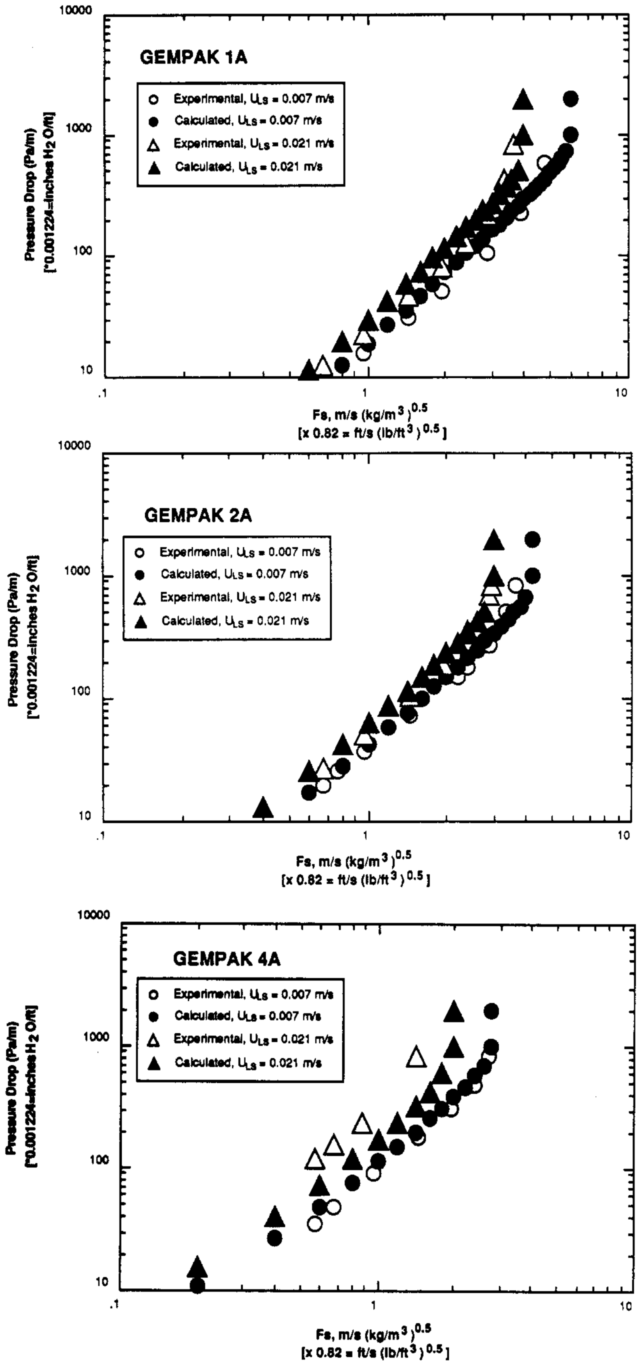

Figure 8. Comparison of measured and calculated values of irrigated pressure drop for Gempak structured packings. Air/water, atmospheric pressure. Equations 20–29 were used for the calculations.

$$AU_{gS}^2 + BU_{gS} - \frac{\Delta P}{\Delta Z}\left\{1 - (0.614 + 71.35S)\left(\frac{4F_t}{S}\right)^{2/3}\left(3\mu_L U_{LS}\Big/\left[\rho_L(\sin\theta)\epsilon g\left[\left(\frac{\rho_L-\rho_g}{\rho_L}\right)\left(1-\frac{\Delta P/\Delta Z}{(\Delta P/\Delta Z)_{\text{flood}}}\right)\right]\right]\right)^{1/3}\right\}^5 = 0 \quad (30)$$

where A, B, and F_t are given by eqs 23a, 23b, and 25, respectively. Thus, by knowing or fixing U_{LS} and U_{gS}, eq 30 has only one unknown ($\Delta P/\Delta Z$) and can be solved more easily than the set of eqs 20–29. Again, the successive or direct substitution algorithm can be used with the dry pressure drop as a good value for the first iteration.

Model Validation—Distillation Data. Distillation tests using structured packings were conducted by the Separations Research Program (SRP) using the cyclohexane/n-heptane system at total reflux and at several different pressures. These tests provided mass-transfer efficiency as well as pressure drop data under actual distillation conditions. Table III summarizes the test conditions used, and Table IV describes the test equipment and the packings involved. A description of the equipment has been given by Fair and Bravo (1990).

The application of the pressure drop model to the SRP data proved to be successful. The results are shown in Figures 10–13. A comparison with predictions using the GPDC model (Leva, 1954; Eckert, 1970), and the works of Bravo et al. (1986) and Stichlmair et al. (1989), is also

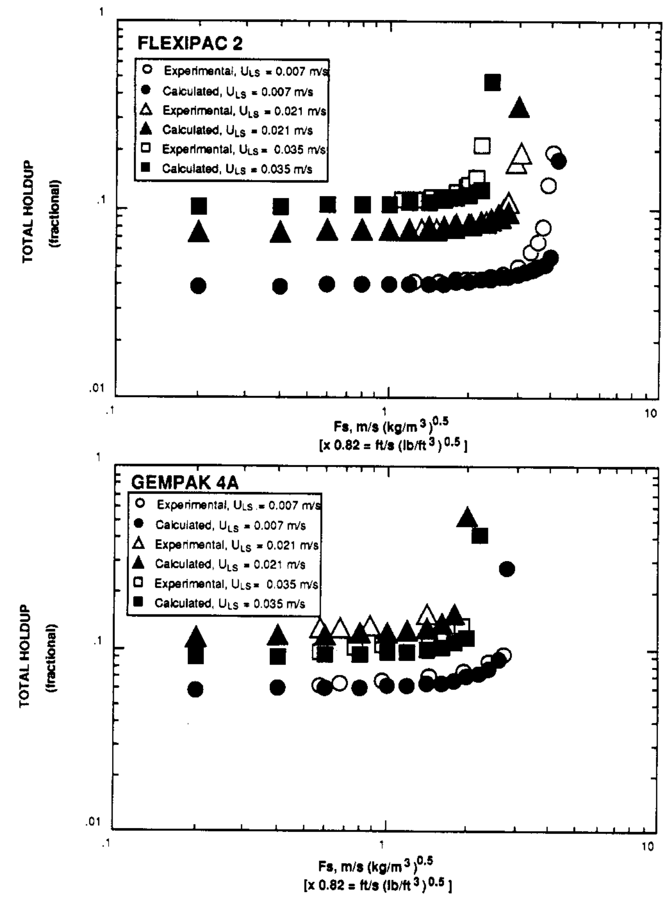

Figure 9. Comparison of measured and calculated values of total holdup for structured packings. Air/water, atmospheric pressure.

Table III. Distillation Conditions for Pressure Drop Tests[a]

pressure (bar)	ρ_g (kg/m^3)	ρ_L (kg/m^3)	μ_g (mPa·s)	μ_L (mPa·s)	σ (N/m)
0.33	1.1	700	0.0074	0.457	0.019
1.63	4.9	690	0.0085	0.280	0.014
4.14	11.7	686	0.0094	0.200	0.010

[a] System: cyclohexane/n-heptane at total reflux.

Table IV. Test Equipment and Packings for Distillation Tests[a]

packings studied	a_p (m^2/m^3)	S (m)	ϵ
Gempak 2A	223	0.018	0.95
Intalox 1T	315	0.0152	0.94
Intalox 2T	213	0.0221	0.95
Jaeger Maxpak	229	0.0175	0.95
Sulzer BX	492	0.009	0.90

[a] Column i.d. = 0.43 m; packing height = 3 m; packing material = 316 SS (sheet or gauze).

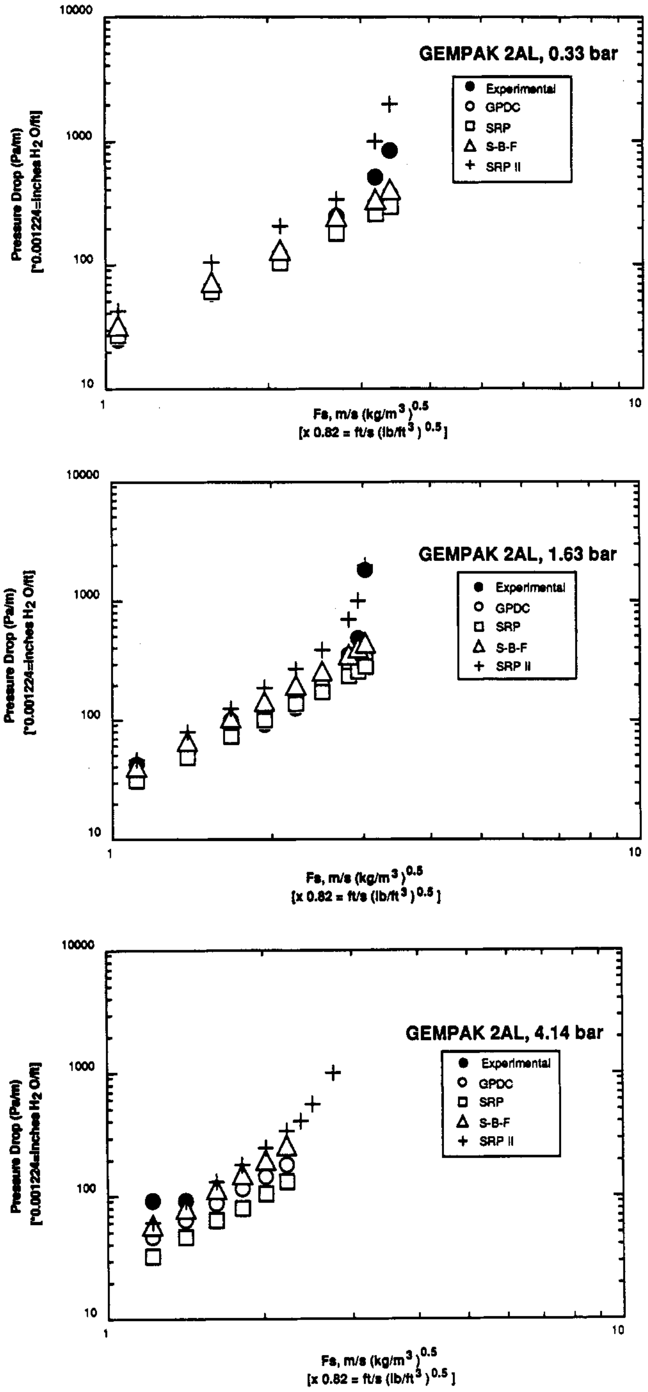

Figure 10. Comparison of measured and calculated values of irrigated pressure drop in distillation service for Gempak structured packings. Cyclohexane/n-heptane at total reflux. GPDC = general-purpose design chart. SRP = Bravo et al. (1986). S–B–F = Stichlmair et al. (1989). SRP II = present work.

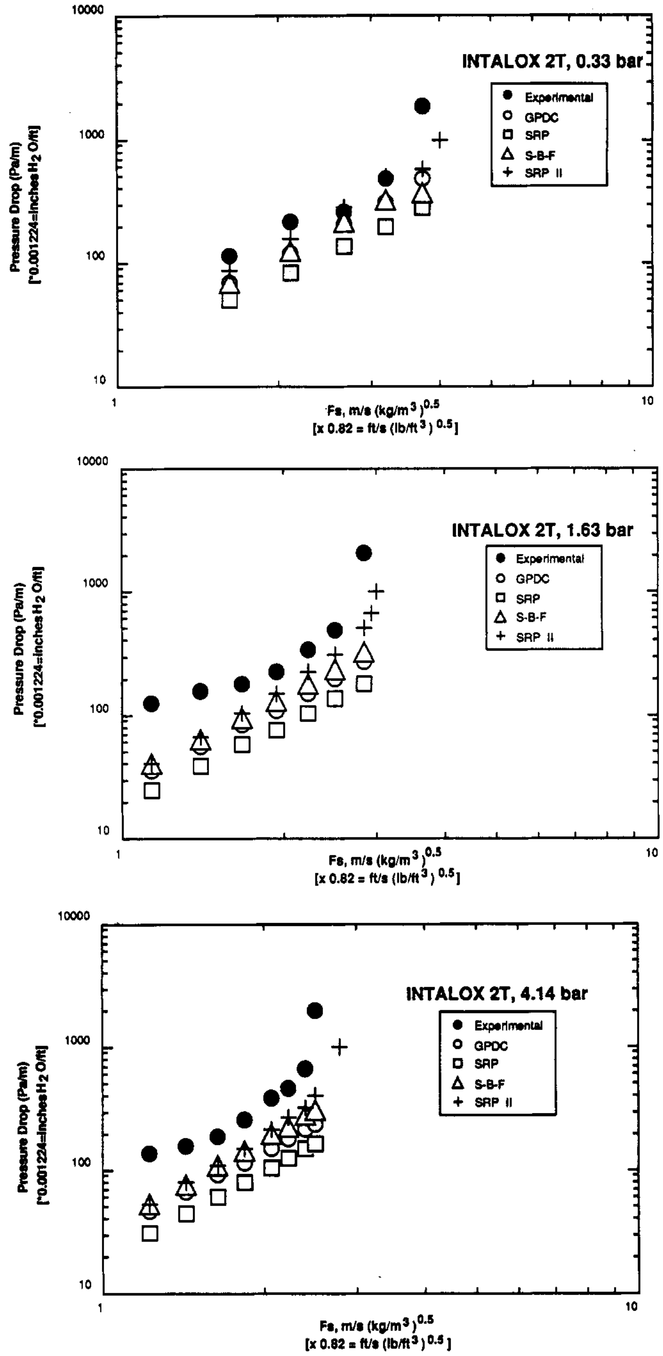

Figure 11. Comparison of measured and calculated values of irrigated pressure drop in distillation service for Intalox structured packings. Cyclohexane/n-heptane at total reflux. GPDC = general-purpose design chart. SRP = Bravo et al. (1986). S–B–F = Stichlmair et al. (1989). SRP II = present work.

shown. The model proposed here does an excellent job of predicting pressure drop up through the loading region. An accurate indication of the flood point is also achieved.

As expected, the GPDC and Bravo et al. models fail to follow the pressure drop curves in the loading region. The Stichlmair model and the one presented here follow the data closely in the loading region by virtue of the inclusion of a variation of holdup with gas load and pressure drop.

It should be noted that the only packing characteristics needed for using the present model are the packing size (side of the corrugation) and the void fraction.

Maximum Capacity. As indicated by the excellent fit of the pressure drop data in the loading region for both the air/water data and the distillation data, this pressure drop model can be used effectively to predict the maximum hydraulic capacity of structured packing. Figures 7–9 indicate that the predictions of the flood point by this model in the air/water system appear reasonable. Figures 10–13 show that the predictions offered by the model for the distillation tests are reasonable as well. The designer can use the model at a fixed liquid rate to find the gas rate at flooding by simply plotting the pressure drop curve at a constant liquid rate for a varying gas rate. The inflection in this curve will provide a value of the flooding gas velocity for the selected liquid rate.

All calculations are based currently on a value of flooding pressure drop of 1025 Pa/m, as used for holdup.

Conclusions—Pressure Drop. A more general model

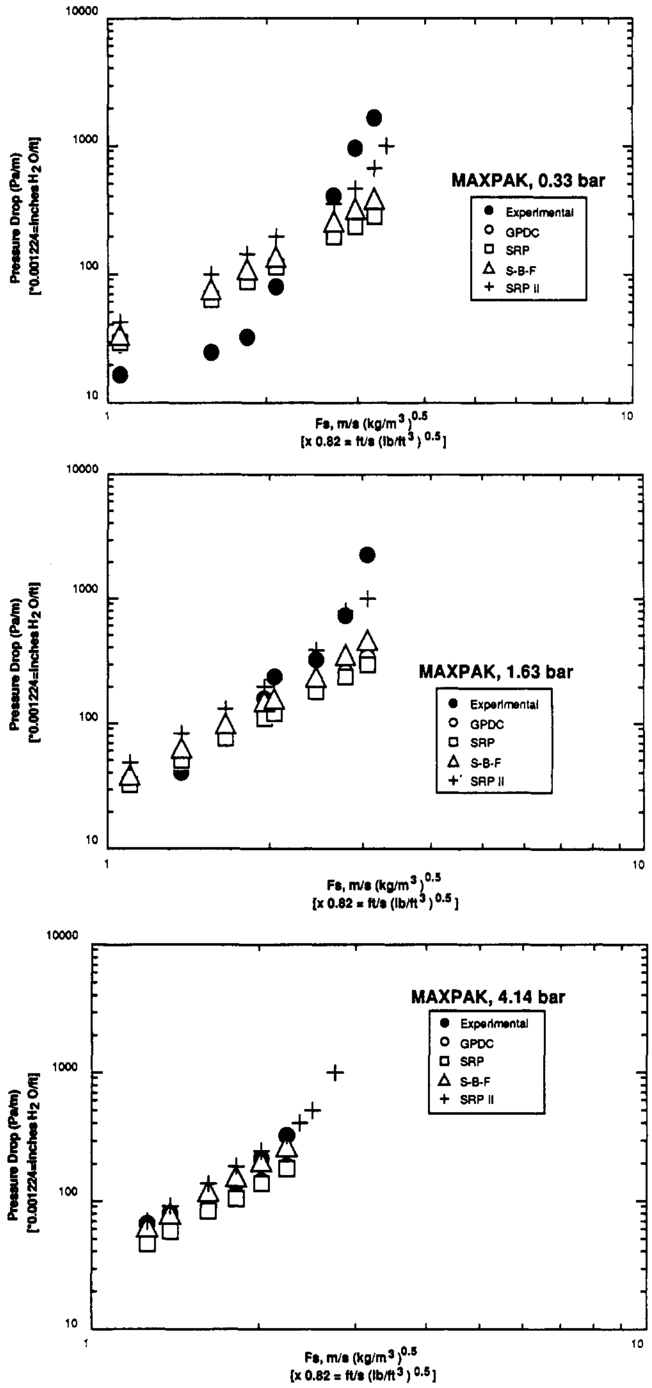

Figure 12. Comparison of measured and calculated values of irrigated pressure drop in distillation service for Maxpak structured packings. Cyclohexane/n-heptane at total reflux. GPDC = general-purpose design chart. SRP = Bravo et al. (1986). S–B–F = Stichlmair et al. (1989). SRP II = present work.

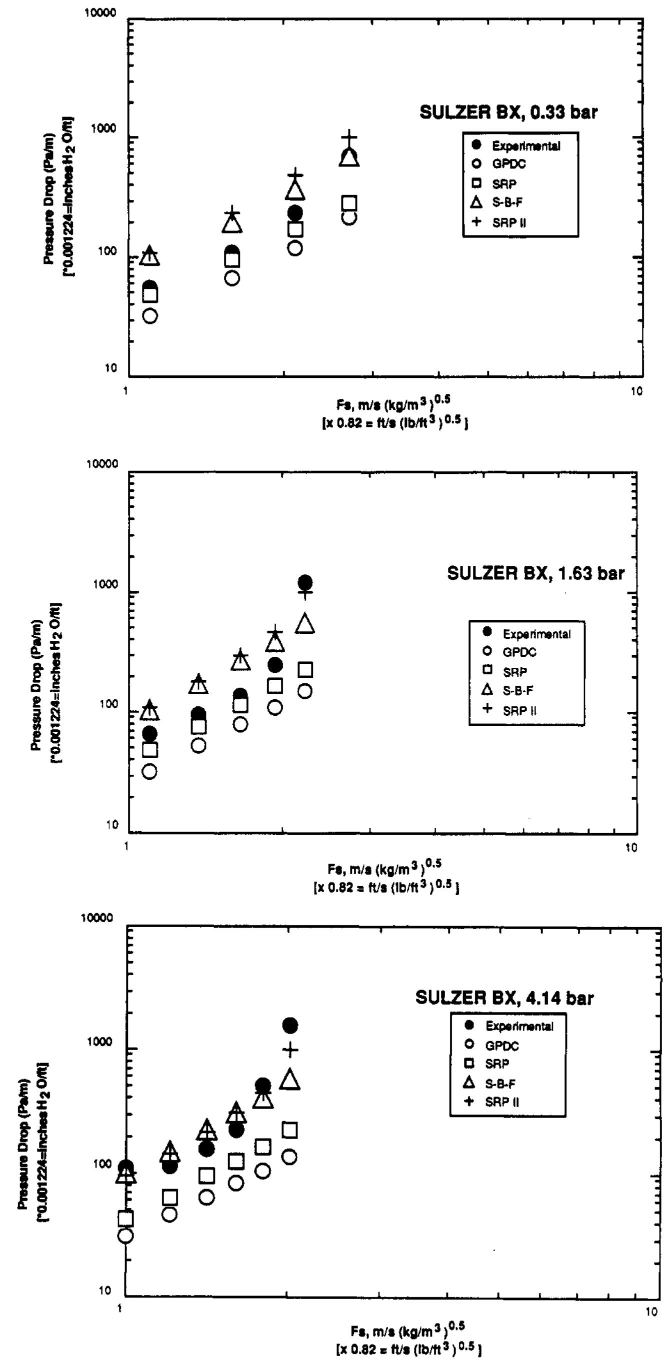

Figure 13. Comparison of measured and calculated values of irrigated pressure drop in distillation service for Sulzer BX structured packings. Cyclohexane/n-heptane at total reflux. GPDC = general-purpose design chart. SRP = Bravo et al. (1986). S–B–F = Stichlmair et al. (1989). SRP II = present work.

for the prediction of pressure drop in structured packings, based on the wetted wall column analogy, has been developed and validated. This model appears to be superior to earlier ones because it is able to predict pressure drop above as well as below the load point. The model was developed using air/water data for several packings and was validated by comparing its predictions with results from actual distillation runs at various pressures.

Comparisons also indicate that the model developed by Stichlmair et al. (1989) using a fluidized bed analogy works well in the complete region but requires the use of several packing-specific constants. The present model requires only a knowledge of the packing dimensions. On the other hand, the present model is useful only for structured packings of the corrugated type, whereas the one by Stichlmair et al. (1989) can be used for random packings as well.

These two pressure drop models are more fundamental in nature than those based on the "packing factor" approach. The latter are easy to use and can be valuable when comparing packings. However, the more fundamental models should prove more useful for detailed design since they can be applied to more extreme conditions.

Summary

A comprehensive model has been developed for predicting the liquid holdup, pressure drop, and flooding capacity for columns containing structured packings of the corrugated metal type. The model is consistent in that the same parameters are used for each of the predicting approaches. It takes into account the texturing of the packing surface as well as the wettability of the surface material when in contact with various types of liquids. It is thus able to differentiate between the interfacial areas generated by flowing aqueous or organic liquids. The model has been validated for air/water as well as organic distillation systems, and for operating pressures ranging from 0.02 to 4.14 bar. The effects of axial mixing under high-pressure operating conditions have been left to the determination of theoretical stages or transfer units but are implicitly included in holdup predictions under high loading conditions and at lower pressures; these effects will be discussed in part 2, which will present a mass-transfer model that is consistent with the hydraulic parameters developed in this part 1.

Nomenclature

A', B' = Shi–Mersmann constants (eq 12), dimensionless
A, B = constants in eq 23, dimensionless
a_e = effective area, 1/m
a_p = packing surface area, 1/m
f = friction factor, dimensionless
F_o = operating holdup correction factor, dimensionless
Fr_L = Froude number for the liquid, dimensionless
F_s = gas flow factor ($=U_{gS}(\rho_g)^{0.5}$), m/[s(kg/m^3)$^{0.5}$]
F_s' = static holdup correction factor, dimensionless
F_t = correction factor for total holdup due to effective wetted area, dimensionless
g = gravitational constant, m/s^2
g_c = gravity conversion factor = 1.0
g_{eff} = effective gravity, m/s^2
h_t = total holdup, dimensionless
h_{op} = operating holdup, dimensionless
h_{stat} = static holdup, dimensionless
K_1 = constant (eq 6), dimensionless
K_2 = correlation constant (eq 20), dimensionless
P = pressure, Pa or bar
ΔP = pressure drop, Pa
ΔP_d = dry pressure drop, Pa
Q = constant relating pressure drop to gravity, dimensionless
Re_L = Reynolds number for the liquid, dimensionless
S = side dimension of corrugation, m
U_{ge} = effective gas velocity, m/s
U_{Le} = effective liquid velocity, m/s
U_{gS} = superficial gas velocity, m/s
U_{LS} = superficial liquid velocity, m/s
U_r = relative velocity, m/s
We_L = Weber number for the liquid, dimensionless
Z = packed height, m
ΔZ = incremental height, m

Greek Letters
γ = contact angle between solid and liquid film, deg
δ = thickness of film, m
Δ = increment
ϵ = void fraction of packing, dimensionless
θ = angle with horizontal for falling film or corrugation channel, deg
μ_g = gas viscosity, kg/(m·s)
μ_L = liquid viscosity, kg/(m·s)
π = 3.14159...
ρ_g = gas density, kg/m^3
ρ_L = liquid density, kg/m^3
σ = surface tension, N/m

Dimensionless Groups
$Fr_L = U_L^2/Sg$ = Froude number for liquid
$Re_L = U_L S \rho_L/\mu_L$ = Reynolds number for liquid
$We_L = U_L^2 \rho_L S/\sigma g_c$ = Weber number for liquid

Subscripts
op = operating
S–M = Shi–Mersmann
stat = static

Literature Cited

Bemer, G. G.; Kalis, G. A. J. A New Method to Predict Holdup and Pressure Drop in Packed Columns. *Trans. Inst. Chem. Eng.* **1978**, *56*, 200.
Billet, R.; Mackowiak, J. How to Use the Absorption Data for Design and Scale-Up of Packed Columns. *Fette Seifen Anstrichm.* **1984**, *86*, 349.
Bird, R. B.; Stewart, W. E.; Lightfoot, E. N. *Transport Phenomena*; John Wiley: New York, 1960; pp 37–42.
Bravo, J. L.; Fair, J. R. Generalized Correlation for Mass Transfer in Packed Distillation Columns. *Ind. Eng. Chem. Process Des. Dev.* **1982**, *21*, 162.
Bravo, J. L.; Rocha, J. A.; Fair, J. R. Mass Transfer in Gauze Packings. *Hydrocarbon Process.* **1985**, *64* (1), 91.
Bravo, J. L.; Rocha, J. A.; Fair, J. R. Pressure Drop in Structured Packings. *Hydrocarbon Process.* **1986**, *56* (3), 45.
Bravo, J. L.; Patwardhan, A. A.; Edgar, T. F. Influence of Effective Interfacial Areas in the Operation and Control of Packed Distillation Columns. *Ind. Eng. Chem. Res.* **1992**, *31*, 604.
Buchanan, J. E. Pressure Gradient and Liquid Holdup in Irrigated Packed Towers. *Ind. Eng. Chem.* **1969**, *8*, 502.
Chen, G. K.; Kitterman, L.; Shieh, J. H. Development of a New Generation of High Efficiency Packing for Mass Transfer Operations. *Chem. Eng. Prog.* **1982**, *79* (9), 48.
Chen, G. K.; Kitterman, L.; Shieh, J. H. "Glitsch High Efficiency Packings—Preliminary Design Information"; Addendum to Glitsch Publication No. 40283, Glitsch, Inc.: Dallas, TX, 1983.
Eckert, J. S. Selecting the Proper Distillation Column Packing. *Chem. Eng. Prog.* **1970**, *66*, (3), 39.
Fair, J. R.; Bravo, J. L. Prediction of Mass Transfer Efficiencies and Pressure Drop for Structured Tower Packings in Vapor/Liquid Service. *Inst. Chem. Eng. Symp. Ser.* **1987**, *No. 104*, A183.
Fair, J. R.; Bravo, J. L. Distillation Columns Containing Structured Packings. *Chem. Eng. Prog.* **1990**, *86* (1), 19.
Kister, H.; Gill, D. R. Predict Flood Point and Pressure Drop for Modern Random Packings. *Chem. Eng. Prog.* **1991**, *87* (2), 32.
Leva, M. Flow Through Irrigated Dumped Packings—Pressure Drop, Loading, Flooding. *Chem. Eng. Prog. Symp. Ser.* **1954**, *50* (10), 51.
McNulty, K.; Hsieh, C. L. Hydraulic Performance and Efficiency of Koch Flexipac Structured Packing. Paper presented at the Fall AIChE National Meeting, Los Angeles, CA, November 1982.
Robbins, L. A., Improve Pressure-Drop Prediction with a New Correlation. *Chem. Eng. Prog.* **1991**, *87* (5), 87.
Sherwood, T. K.; Shipley, G. H.; Holloway, F. A. L. Flooding Velocities in Packed Columns. *Ind. Eng. Chem.* **1938**, *30*, 765.
Shi, M. G.; Mersmann, A. Effective Interfacial Area in Packed Columns. *Ger. Chem. Eng.* **1985**, *8*, 87.
Spiegel, L.; Meier, W. Correlations of the Performance Characteristics of the Various Mellapak Types (Capacity, Pressure Drop, Efficiency). *Inst. Chem. Eng. Symp. Ser.* **1987**, *No. 104*, A203.
Stichlmair, J.; Bravo, J. L.; Fair, J. R. General Model for Prediction of Pressure Drop and Capacity of Countercurrent Gas/Liquid Packed Columns. *Gas Sep. Purif.* **1989**, *3*, 19.

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