Stretching the Capacity of Structured Packings[†]

Z. Olujic,*[,‡] H. Jansen,[§] B. Kaibel,[§] T. Rietfort,[§] and E. Zich[§]

Laboratory for Process Equipment, Delft University of Technology, 2628 CA Delft, The Netherlands, and Julius Montz GmbH, Hofstrasse 82, Hilden 40723, Germany

Comprehensive experimental and modeling studies conducted recently with various types and sizes of Montz structured packing have revealed most performance-related secrets of this gas−liquid contacting device. Compared with other established gas−liquid contacting devices, structured packings are generally known as having the lowest pressure drop per theoretical tray. Less known is the fact that only a small fraction of this low-pressure drop is used in mass-transfer processes. Knowing this and using a model capable of describing realistically the relationship between geometric features and fluid mechanics, we have manipulated the geometry of the packed bed to develop configurations that allow a substantial increase in capacity without affecting efficiency adversely. The resulting configurations were tested experimentally and a joint experimental and modeling effort by the Delft University of Technology and J. Montz GmbH has led to increased capacity of well-established 45° corrugated sheet packings.

Introduction

Structured packings with 45° corrugation angles represent a well-established and widely used family of gas/liquid-contacting devices. Total reflux distillation performance characteristics of the first generation of these packings have been investigated at a semi-industrial scale, but only a limited number of proprietary data collected by the Separations Research Program (SRP) at the University of Texas at Austin have been published.[1] Over the years, the first of this family, Sulzer's Mellapak 250 Y, has undergone also a number of large-scale studies under total reflux conditions, performed and documented by Fractionation Research Inc. (FRI).[2] Because FRI limits itself to testing commercial packings, its outstanding potential and facilities are not used to support packing development work. Fortunately, a recent comparison of the data obtained with the same type and size of packing under the same operating conditions, using the 1.2-m i.d. FRI column and the 0.43-m i.d. SRP column, has shown that the smaller column provides performance data usable for the design of industrial-scale columns.[3] This finding gave an additional impulse for the development work described in this paper, motivated by market-driven needs to process more feed in existing columns.

Some 10 years ago, following the need for further capacity increases, the response of the packing manufacturers was to increase the corrugation inclination angle of the packing, and a standard size "high capacity" angle of 60° has been established. The performance characteristics of both conventional 45° and 60° Montz packings were thoroughly investigated at the semi-industrial scale. Hydraulic studies were carried out with air and water at ambient conditions using installations available at Delft and at Montz in Hilden, Germany.[4] Total reflux distillation experiments were carried out at SRP using the cyclohexane/*n*-heptane system at various operating pressures (0.33−4.14 bar). The resulting data[5] provide insight into the nature and the effect of corrugation angle, specific surface area, and surface texture on pressure drop, capacity, and efficiency. These data were used as the basis for development of a general correlation for predicting the loading point and the enhancement of pressure drop in the loading region[6] and, most recently, the data were used for validation of SRP and Delft predictive models.[7]

Indeed, if the corrugation angle of structured packing is increased to 60°, the capacity increases significantly, but the percentage capacity gain is roughly equal to the percentage decrease in mass-transfer efficiency.[5−7] This fact made revamping the existing columns equipped earlier with a 45° packing not feasible.

Consequently, a new target was set: to develop a packing with the efficiency of a 45° packing and a capacity of a 60° packing. The pioneer in this field, Sulzer Chemtech, pursued this idea and in the mid-1990s proposed a conceptually new design called Optiflow.[8] Proprietary tests indicated a considerable performance enhancement potential with capacity increases because abrupt flow direction changes were avoided. Mass-transfer performance was good, but appeared possible only at rather low liquid loads. This observation, coupled with a limited flexibility and relatively high manufacturing cost, hampered a wider application of this highly open packing.

This development and increased market pressure directed attention back to the improvement of existing packings, with the less ambitious but still quite optimistic goal of arriving at a substantially increased capacity without loss of efficiency. The performance of standard packings was re-evaluated and excessive liquid accumulation at the interface between packing elements (at gas loads in the loading region), observed by Suess and Spiegel,[9] was identified as a limiting factor for capacity enhancement.

As summarized most recently in *Chemical Engineering*,[10] packing manufacturers have made simple but effective changes in the geometry at the top and/or bottom ends of each element of the standard packings. Proprietary designs are illustrated schematically in

* To whom correspondence should be addressed. Tel.: +31 15 278 6674. Fax: +31 15 278 6975. E-mail: z.olujic@wbmt.tudelft.nl.

† Based on a paper presented in Distillation Honors Session, Honoree J. R. Fair, AIChE Annual Meeting, Los Angeles, CA, Nov 2000.

‡ Delft University of Technology.

§ Julius Montz GmbH.

10.1021/ie010323j CCC: $20.00
Published on Web 12/04/2001

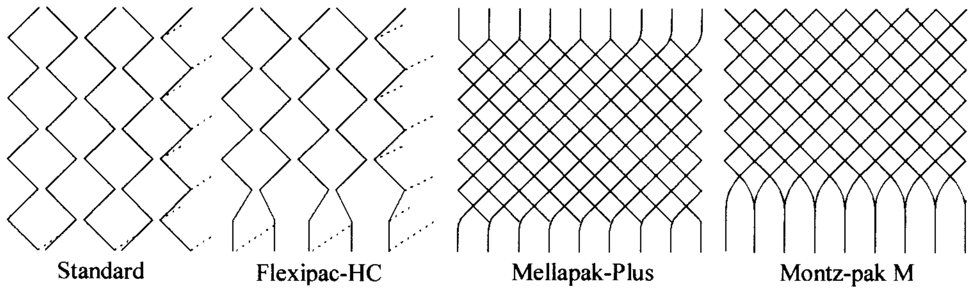

Figure 1. Schematic illustration of proprietary designs of the new generation of high-performance structured packings.

Figure 1. Koch-Glitsch has introduced FLEXIPAC-HC, which differs from the original Flexipac only in the bottom part of each element, where approximately 20 mm of each corrugated sheet is flattened to provide increased hydraulic diameter and to enable a smoother flow direction change for the gas phase. This packing is a spin-off of the original invention by Billingham and Lockett,[11] who demonstrated, on small-scale total reflux experiment, with argon/oxygen and large specific surface area packings, that it is indeed possible to increase capacity without adversely affecting efficiency. A similar effect may be expected from Sulzer MELLAPAK-PLUS. This packing differs from its conventional counterpart in that that the top and bottom ends of each corrugated sheet are bent to be vertical, creating a relatively short transition zone with practically vertical walls. The published performance curves[12] indicate a larger capacity increase than that suggested by Billingham and Lockett who used a larger specific surface area. However, experimental evidence from independent sources, under distillation conditions, has not yet been provided; this is needed if the advertised performance of these new, high-capacity packings is to be confirmed.

The pesent paper describes modeling and experimental efforts undertaken jointly by the Delft University of Technology and J. Montz GmbH. It also introduces a new high-capacity packing that evolved from an appropriate modification of the corrugation geometry of a Montz gauze packing introduced in the early 1980s. As indicated schematically in Figure 1, and shown clearly in the photograph in Figure 2, the major feature of the Montz B1-M series is a long, smooth bend in the bottom part of the corrugation with continuously increasing corrugation base width. With this simple modification of the bottom part of the element, a considerable increase of capacity can be achieved with only a small loss of efficiency that is limited mainly to the preloading region.

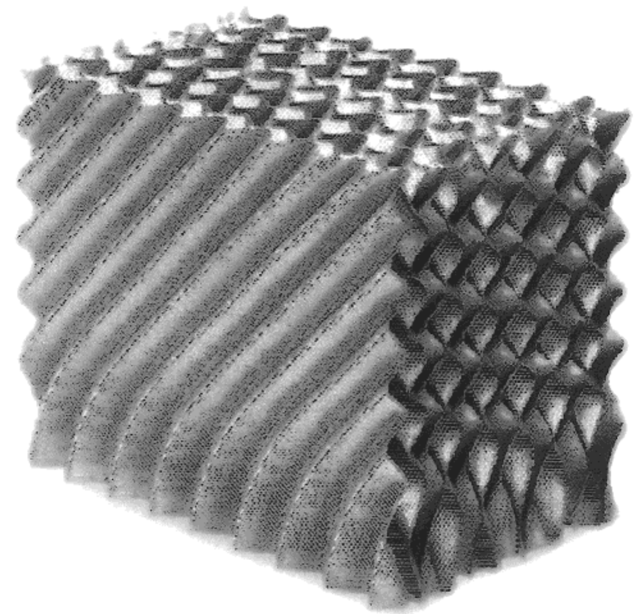

Figure 2. Photograph of a segment of J. Montz high-capacity packing B1-250M.

Background

In a bed of structured packing (see Figure 3), the elements/layers are stacked such that each subsequent element is rotated 90° with respect to the previous one. This implies that the ascending gas is forced to make a sharp change in flow direction at each transition between elements. This also occurs with gas flow channels ending at the column walls. As established in our packing hydraulics studies, and taken into account in the Delft model,[13,14] the resulting pressure loss comprises three major components: gas−liquid interaction on the surface of the liquid film covering the surface, losses related to abrupt direction changes at the transitions, and losses due to interaction of gas streams at open crossings of gas flow channels. The latter, much less obvious than the other two, appeared to be responsible for considerable pressure loss of conventional 45° packing and together with the other major component—direction change losses—does not participate significantly in the mass-transfer process. This became obvious after evaluating the results of a comprehensive total reflux distillation study of Montz packings in cooperation with SRP at the University of Texas.[5] Considerable research effort oriented toward searching for a simple but effective macro geometrical

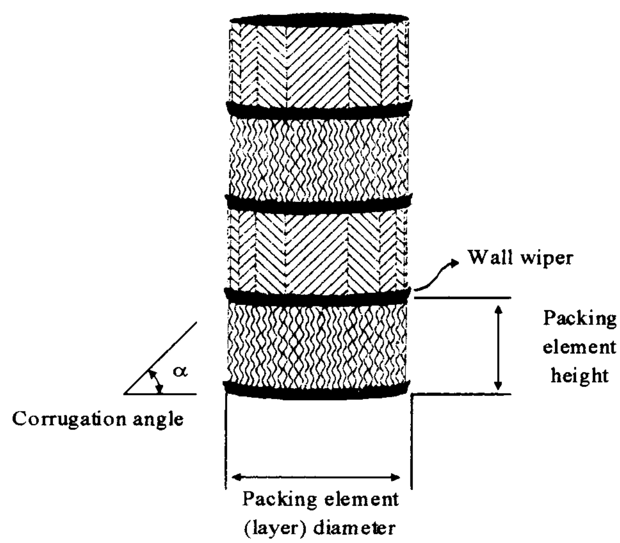

Figure 3. Schematic illustration of a structured packing bed.

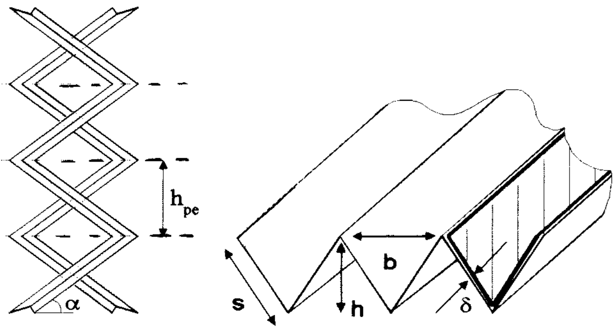

Figure 4. The form of gas flow channels and characteristic dimensions of corrugated sheets.

Table 1. Corrugation Geometry-Related Parameters

specific surface area of packing:

$$a_p = \frac{4s}{bh} = \frac{2\sqrt{b^2 + 4h^2}}{bh} \quad (1)$$

hydraulic diameter for gas in a dry triangular channel:

$$d_{hG,dry} = \frac{2bh}{b + 2s} = \frac{2bh}{b + \sqrt{b^2 + 4h^2}} \quad (2)$$

V-shaped fraction of the gas flow channel:

$$\varphi = \frac{2s}{b + 2s} = \frac{\sqrt{b^2 + 4h^2}}{b + \sqrt{b^2 + 4h^2}} \quad (3)$$

(flow channel) structure, that is, one that would allow maximization of the ratio of "useful" to "useless" pressure drop, preceded publishing the results.

Macro Geometry of a Corrugated Sheet Structured Packing

The main geometry-related parameters of a corrugated sheet structured packing are the specific surface area, a (1/m), void fraction or porosity, ϵ (m^3/m^3), and the corrugation angle inclination, α (deg). Figure 4 illustrates schematically the zigzag nature of crossing triangular gas flow channels formed between adjacent corrugated sheets and shows the major dimensions of the corrugations. As can be seen from characteristic expressions shown in Table 1, the amount of specific surface area, the hydraulic diameter for gas-phase flow under dry conditions, and the V-shaped fraction of a triangular cross section occupied by corrugation sides are all directly related to the corrugation base length, b (m), and corrugation height, h (m). These can be accurately measured for each set of packings.

The corrugation height-to-base ratio is usually around 0.5, which corresponds to a crimp angle β of 90°. As indicated in Figure 4, the gas flow channels are triangular, with two sides covered by liquid film and the third side open to the open side of the crossing gas flow channels from the adjacent sheet. The channel length is relatively short because of the low height of packing elements in the range of 0.15−0.30 m. Obviously, the hydraulic diameter for the gas in an irrigated bed depends on the thickness of the liquid film, δ (m). Liquid holdup measurements have indicated that the theoretically based Nusselt formula for the thickness of falling laminar films, adapted accordingly for inclined walls, represents the situation encountered in practice with common metal sheet packings. This equation together with eqs 1−3 and the expressions for other relevant geometry- and flow-related parameters that are summarized in Tables 2 and 4 in the paper by Fair et al.[7] represent the basis of the overall Delft model for predicting the hydraulic and mass-transfer performances of corrugated sheet structured packings.

Table 2. Characteristic Dimensions of the Base-Case Packing Montz-Pak B1-250

specific surface area (a_p)	250 m^2/m^3
packing element height (h_{pe})	0.197 m
porosity (ϵ)	0.98
corrugation angle (α)	45°
crimp angle (β)	90°
corrugation base (b)	0.0226 m
corrugation side (s)	0.0160 m
corrugation height (h)	0.0113 m
V-shaped wall fraction of a triangular channel (φ)	0.586 m
hydraulic diameter for gas (d_{hG})	0.0094 m

Table 2 contains rounded values of major dimensions of Montz-Pak B1-250, a well-known corrugated sheet structured packing with an unperforated and shallow embossed surface, which is used as the base case throughout this study. Note that dimensions of various sets of packings vary slightly. For instance, the specific surface area is 244−256 m^2/m^3, which is a consequence of small variations (within manufacturing tolerances) in corrugation dimensions.

Delft Model Refinements

With respect to the first published version of the Delft model,[13,14] the latest version[7] contains new, generally valid correlations for determination of loading point and the effect of loading on pressure drop,[6] which take into account the effects of corrugation angle and packing size. This is important because the shift in the loading point gas load represents an indication of the corresponding capacity variations.

An important generalization step is the adoption of the well-known Onda et al.[15] correlation for predicting the effective area of structured packing in conjunction with a correction term accounting for the reduction in available surface proportional to the void fraction. As shown elsewhere,[7] the Onda et al.[15] correlation with hydraulic diameter for gas as the characteristic linear dimension in the liquid-phase Reynolds, Weber, and Froude numbers reproduces fully the experimental results. To ensure a more conservative prediction in the region of low liquid loads, where rivulet formation leads to a pronounced loss of wetted area, the present version of the Delft model utilizes the specific surface area of packing as a characteristic linear dimension.

Another fundamentally sound extension of the Delft model is the use of an effective liquid flow angle, which follows from a theoretically founded relationship[16−18] including corrugation angle, corrugation base width, and corrugation height. For the 45° packing the effective liquid flow angle is 53.9°, and for the 60° packing it is 67.2°. However, the increase in flow angle with respect to the vertical axis by 9° and 7° has only a slight deteriorating effect on mass-transfer efficiency.

Working expressions are summarized in Table 3. Most importantly, with these extensions the Delft method does not require any empirical, packing-specific coefficient. Thus, it allows full freedom regarding the variations of packing geometry. This will be discussed in more detail when appropriate, that is, in later paragraphs describing the effects of geometry variations evaluated in this study.

Table 3. Working Equations for the Effective Surface Area and the Effective Liquid Flow Angle

Effective Surface Area

extended Onda et al.[15] correlation with specific surface area (original) as characteristic length dimension:

$$a_e = a_p(1 - \Omega) \times \left\{1 - \exp\left[-1.45\left(\frac{0.075}{\sigma}\right)^{0.75} Re_L^{\,0.1} Fr_L^{\,-0.05} We_L^{\,0.2}\right]\right\} \quad (4)$$

with

$$Re_L = \frac{\rho_L u_{Ls}}{a_p \mu_L} \quad (5)$$

$$We_L = \frac{\rho_L u_{Ls}^{\,2}}{a_p \sigma} \quad (6)$$

$$Fr_L = \frac{u_{Ls}^{\,2} a_p}{g} \quad (7)$$

where Ω (−) stands for the fraction of surface area occupied by holes and/or other apertures not covered by liquid during operation

Effective Liquid Flow Angle

$$a_{Le} = a\tan\left[\frac{\cos(90 - \alpha)}{\sin(90 - \alpha)\cos\left[a\tan\left(\frac{b}{2h}\right)\right]}\right] \quad (8)$$

Performance Enhancement Approaches

As indicated earlier, gas−gas interaction and direction change related energy losses, which together make up more than 80% of the total pressure drop in a 45° packing, may be considered as not useful for mass transfer. In other words, a reduction or elimination of one of these components should allow a capacity increase without significant efficiency penalty. In what follows, an overview is given of the potential for performance improvement for four different modifications of geometry, as estimated by the Delft method. The first two are related to elimination/reduction of the gas−gas interaction, and the latter two are related to the direction change in gas flow at the transition between packing layers.

Elimination of Gas−Gas Interaction

An evident approach is to avoid contact of crossing gas streams by inserting flat sheets between corrugated sheets. This is illustrated schematically in Figure 5 for the case having the same size of corrugations (modification A) and the case with the same amount of surface area (modification B), that is, correspondingly larger corrugation dimensions. In this way the structure of a common corrugated sheet packing is transformed into a monolith-like structure with a multiplicity of closed inclined flow channels.

When a flat sheet is placed between two corrugated sheets, the installed specific surface area of the original packing increases substantially. This implies a pressure drop increase roughly proportional to the increase in surface area, which if wetted completely could lead to a substantial increase in mass-transfer efficiency, that is, a correspondingly smaller HETP value. In other words, with this rather simple packing modification it appears possible to reach two objectives in one move, considerable reduction in both the total pressure drop and the HETP value.

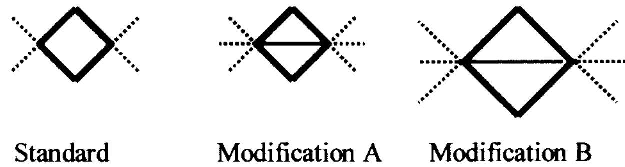

Figure 5. Schematic illustration (top view) of standard and the monolith-like structured packings.

Table 4. Comparison of Predicted Performances of Conventional Packing and Two Monolith-like Modifications (Cyclohexane/*n*-Heptane, 1.03 bar, d = 0.43 m, $h_{pb} \approx$ 3.3 m, F_G = 1.5 m/s (kg/m³)$^{0.5}$)

packing version	a_p (m²/m³)	h (m)	b (m)	HETP (m)	$\Delta p/\Delta z$ (mbar/m)	$F_{G,lp}$ (m/s (kg/m³)$^{0.5}$)
standard	250	0.0113	0.0226	0.39	0.89	1.89
modif. A	398	0.0113	0.0226	0.17	0.59	1.89
modif. B	250	0.0192	0.0384	0.30	0.44	2.56

To obtain an indication of achievable gains in capacity and/or efficiency, the Delft model was adapted accordingly. The gas−gas interaction coefficient in the overall pressure drop equation was set equal to zero, and the factor describing the fraction of the wall in contact with gas flow was set to a value of 1. The same assumption was made for irrigated packing, implying that the installed surface area will be wetted according to eq 4.

The results of model predictions are summarized in Table 4 and indicate the theoretical limits for the performance improvement potential in this case. Modifications “A” and “B” refer respectively to monolith-like packings with the same corrugation dimensions (larger surface area) and the same total surface area (larger corrugation dimensions).

A more than halved HETP value in the case of packing “A” is the consequence of an addition to the efficiency enhancement proportional to surface area increase. There is also a significant mass-transfer enhancement due to an increased gas-phase Sherwood number. The latter results from the fact that now all three sides of triangular gas flow channel are involved in the mass-transfer process. This is also the reason the predicted HETP value in the case of the same surface area (modification B) is lower than that of the original packing. In addition, in this case the flow channel length-to-diameter ratio is quite low; however, the enhancement due to entrance effects is pronounced in the low *F*-factor region only, where laminar flow conditions predominate.

The extent of pressure drop reduction is striking. For modification A the reduction is equivalent to the gain resulting from the fact that with the insertion of a flat sheet between two corrugated sheets the energy-consuming gas−gas interaction is replaced with a less energy-consuming gas−liquid interaction. The additional pressure drop reduction for modification B is attributed simply to a significantly larger hydraulic diameter of the gas flow channel. For the same reason the capacity of this packing is considerably larger than that of modification A and standard designs. This is illustrated by the corresponding difference, that is, shift in the values of the “loading point gas load”, F_{Glp}, which is a good indication for relative gains or losses in capacity. Although modification A produces less pressure drop than standard packing, there is no difference in the value of the loading point gas rate. This is simply because of the same value of the hydraulic diameter for

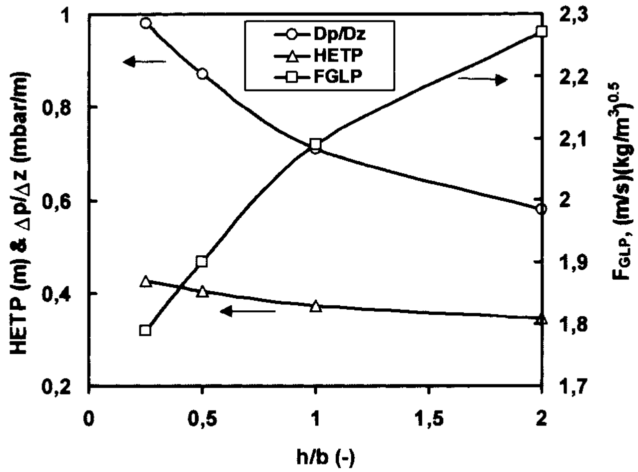

Figure 6. Predicted effect of the corrugation height-to-base ratio (cyclohexane/n-heptane, 1.03 bar, d = 0.43 m, $h_{pb} \approx$ 3.3 m).

the gas, which is the characteristic geometry parameter in the loading point correlation.

Increasing the Corrugation Height-to-Base Ratio

From the above considerations it seems clear that the key to performance enhancement is the enlargement of gas–liquid (skin) friction with respect to relatively useless gas–gas interaction. As illustrated in Figure 6, another rather simple way to reach this is to increase the corrugation height-to-corrugation base ratio, usually about 0.5 or less. In this case, the model suggests a significant pressure drop decrease accompanied by an appreciable capacity increase, both mainly due to an increasing hydraulic diameter for the gas. Going from 0.5 to 1 means a pressure reduction by roughly 20% and a capacity gain of roughly 10%. Air/water experiments carried out in a 0.2-m i.d. column with a handmade prototype confirmed this. This rather simple packing modification, described in detail in the Ph.D. thesis by Woerlee,[19] has been patented recently.[20]

According to Figure 6, the model suggests also a slight improvement in efficiency with increasing height-to-base ratio, proportional approximately to the resulting increase in the hydraulic diameter. However, in reality, one can expect that mass-transfer efficiency will be affected adversely because of liquid spreading (pronounced rivulet formation) related problems.

Augmentation of Direction Change Angle

A significant reduction of useless pressure drop can also be achieved by making the inlet and outlet ends of the packing rounded to avoid sharp bends at transitions between packing elements. This can be achieved either by arranging a packed bed to consist of standard packing elements separated by short elements with vertically oriented corrugations, as illustrated schematically in Figure 7a, or by bending smoothly the lower parts of corrugations to be vertical (see Figures 1 and 2).[21] In both cases the direction change angle is enlarged from 90° (2 × 45°) to 135° (90° + 45°), but in the first case this is at the expense of doubling the number of bends in gas flow along the bed.

Table 5 shows predictions for a preloading region gas load and a constant liquid load for common 45° and 60° packings for a bed including short vertical elements (B1-250+B1V) and for the new packing with the smooth bends (B1-250M) in the bottom parts of the corrugations.

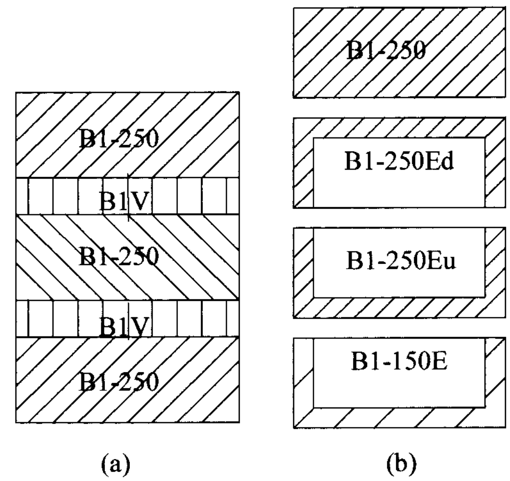

Figure 7. Packing element/bed configurations considered in this study. White surfaces in (b) indicate the relative size and position of flat sheets inserted between the corrugated sheets.

Table 5. Predicted Effect of the Enlargement in the Angle of Flow Direction Change at the Transition between Packing Elements (Air/Water, u_{Ls} = 10 m³/m² h, F_G = 1.5 m/s (kg/m³)$^{0.5}$)

configuration	α_{DC} (deg)	$\Delta p/\Delta z$ (mbar/m)	$F_{G,lp}$ (m/s (kg/m³)$^{0.5}$)
B1-250	90	1.05	2.41
B1-250.60	120	0.36	2.83
B1-250+B1V	135	0.76	2.96
B1-250M	135	0.76	2.96

As indicated in Table 5, for a larger angle of the flow direction change, the model predicts a significant pressure drop reduction, accompanied by an appreciable increase in capacity. Expressed in numbers, this means for both configurations a nearly 30% decrease in pressure drop accompanied by a capacity gain of ≈20%.

It should be noted that two configurations were modeled by adjusting the gas flow angle in the expressions describing the direction change related pressure drop. In the bed containing vertical elements the pressure drop due to friction comprised components covering flow through respectively inclined and vertical channels, with the total flow channel length equal to the sum of inclined and vertical parts. On the other hand, the total length of the flow channel in the packing with a smooth bend in the corrugations was reduced accordingly (by 5%). The effect of smooth bends was neglected and the contribution of gas/gas interaction reduced accordingly. Namely, it was assumed that through a bend in the lower part of the corrugated sheets (one-third of the packing element height) roughly 30% of the crossings of gas flow channels would be eliminated in comparison with the common situation. Corresponding reduction in the gas/gas interaction contribution delivered practically the same pressure drop for both configurations. One may note that in the case of the vertical/inclined combination a doubled number of bends has been taken into account. With only one bend per combination the total pressure drop would drop by 5%. Because the angle of gas flow direction change is the same in both cases, the capacity of both configurations should be the same and correspondingly larger than that of a 60° packing. On the other hand, the predicted pressure drop of a 60° packing is much lower, which is a consequence of the correspondingly large reduction in the gas/gas interaction related pressure drop.

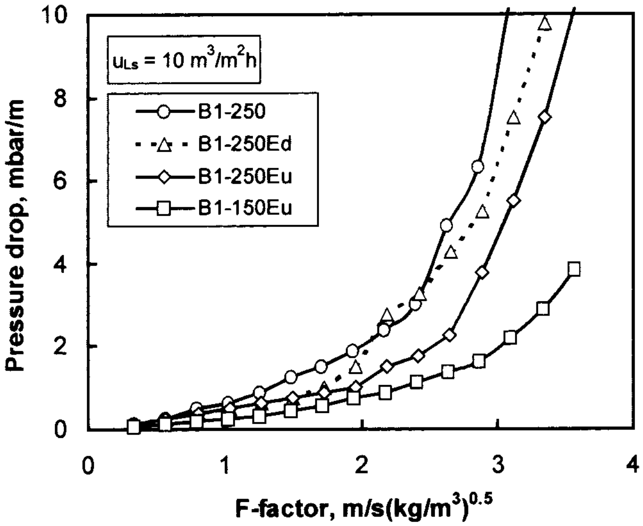

Figure 8. Effect of the packing element configuration on pressure drop (air/water, 1.013 bar, d = 0.45 m, $h_{pb} \approx 0.8$ m).

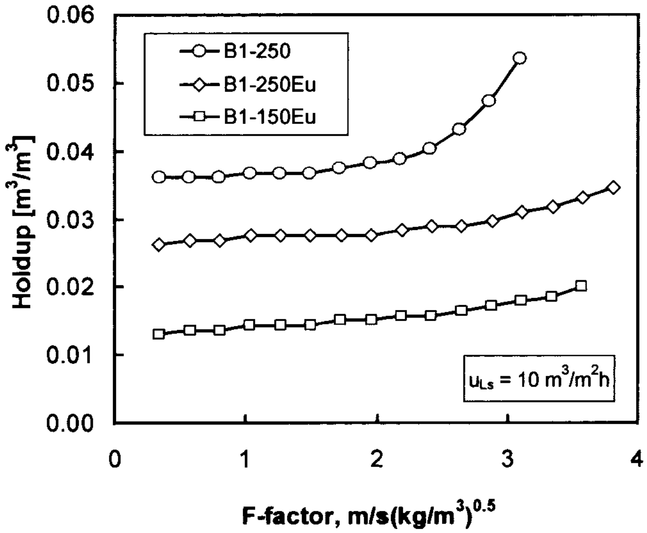

Figure 9. Effect of the packing element configuration on liquid holdup (air/water, 1.013 bar, d = 0.45 m, $h_{pb} \approx 0.8$ m).

As usual, in this and other cases model predictions have been considered only as rough indications and most promising configurations have undergone a series of hydraulic tests. This finally led to a limited number of configurations, which were then exposed to total reflux distillation tests.

Experimental Method

A detailed description of the hydraulic test equipment at Delft and at Montz may be found in a recent paper describing the effect of the column diameter on the pressure drop of a corrugated sheet structured packing.[14] The results in this paper covered pressure drop, capacity, and liquid holdup under ambient conditions.

Total reflux distillation experiments were carried out at SRP in a column with an internal diameter of 0.43 m and with use of the cyclohexane/*n*-heptane system. In all cases the packed height was around 3.3 m. The operating pressure was varied from 0.33 to 4.14 bar to determine the effects of physical properties and increasing liquid load. However, in this paper we will consider only the atmospheric pressure data, to be compatible with the results of air/water tests. A detailed description of the experimental setup and procedure employed at SRP can be found elsewhere.[5]

Results and Discussion

For the sake of simplicity, in the simulation effort the size of inserted flat sheets has been assumed equal to the size of neighboring corrugated sheets. Because this can cause liquid buildup and drainage problems at the transitions between packing layers and in the wall zone, the prototype packing was provided with properly dimensioned and positioned flat sheets.[22] Two different configurations of modification A were tested, one with sandwiched flat sheets in the lower part of the packing element (B1-250Ed) and the other with flat sheets in the upper part of the element (B1-250Eu). The latter has also been used with modification B (B1-150Eu), the monolith-like packing with corrugation dimensions corresponding to that of conventional packing with a specific surface area of 150 m^2/m^3. These configurations, illustrated schematically in Figure 7b, were compared to standard packing. The pressure drop curves for air/water at ambient conditions, in a 0.45-m column, are shown in Figure 8.

In the preloading region, both versions of modification A, with ≈45% larger surface area, produced a considerably lower pressure drop than the standard packing. Strikingly, the onset of loading appeared to depend on the positioning of the flat sheets. The configuration with flat sheets in the bottom part of the packing element appeared to load much earlier than the standard and the upside-down configurations. This observation was of particular importance because it clearly indicated the bottom part of a packing element as a bottleneck for transport of gas and liquid at the transition between elements. The configuration with flat sheets in the upper part reached a pressure drop of 2 mbar/m at a 30% higher value of F factor than the standard one, which indicates that this modification allows operation at correspondingly larger capacity. Even a larger capacity increase (around 50%) can be expected from the modification with larger corrugations, that is, from a larger hydraulic diameter.

As illustrated in Figure 9, this achievement was partly due to a rather large reduction in liquid holdup, which indicated indirectly that a certain degree of efficiency loss might be expected from the modified packing. It turned out to be even worse, as might be conjectured from the comparison of total reflux distillation performances of standard and enlarged surface area packings with flat sheets in the upper part of packing elements (Figure 10). The culprit here was liquid maldistribution. Because of the closed channel structure in the upper part of packing element, the first packing element did not function as a liquid redistribution element. Only a few of the channels receive the liquid. In addition, because of the presence of a flat sheet between the corrugated sheets, strong liquid mixing at crossings of corrugated sheets is completely avoided and can occur only at the transition between packing layers. A rather strong improvement in packing performance with increasing F factor, reaching that of the standard design in the loading region, can be attributed to the increase in the extent of lateral spreading at the transitions of packing layers.

The fact that the best performance reached in the loading region is equal to that of standard packing indicates that the much larger installed surface area is not used fully. For the modified packing, liquid cannot

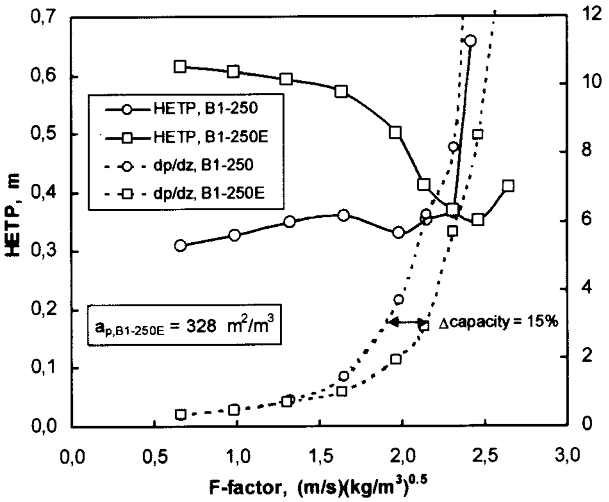

Figure 10. Comparison of total reflux distillation performances of common type and monolith-like packings (cyclohexane/n-heptane, 1.03 bar, d = 0.43 m, $h_{pb} \approx$ 3.3 m).

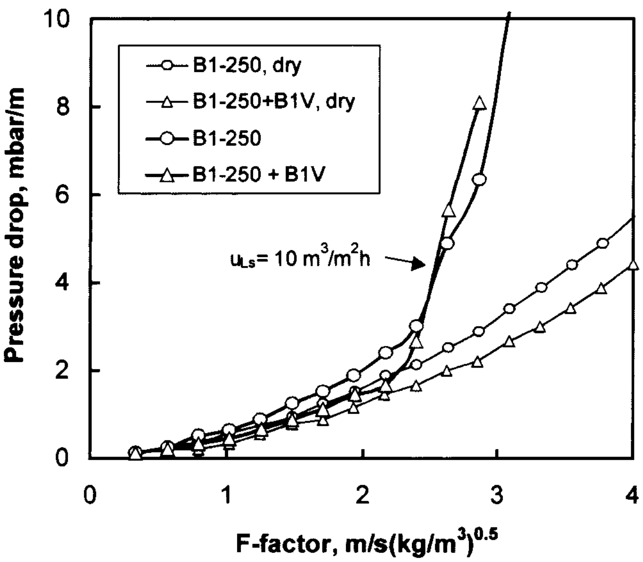

Figure 11. Pressure drop of a bed consisting of conventional B1-250 packing elements separated by short elements consisting of vertical corrugated sheets (air/water, 1.013 bar, d = 0.45 m, $h_{pb} \approx$ 2 m).

leave or enter a closed channel and tends to form rivulets along the lowest edge of the triangular channel. This indirectly indicates the importance of open communication between crossing sheets for surface wetting and renewal within a packing element. In the case of the standard packing, increasing gas load leads to the suppression of the spreading of liquid over the corrugation ridges. This appears to be the reason for the deteriorating trend in efficiency of standard packings, but which turns into an improvement upon reaching the point of onset of loading regime. This more or less pronounced trend in mass-transfer enhancement lasts until the onset of flooding is reached.

Although mass-transfer performance appeared rather poor, the monolith-like structure with a much larger surface area enabled operation at an appreciably larger gas load, indicating that pressure drop related to gas/gas interaction also influences the capacity to a greater extent.

Figure 11 shows the effect of increasing the flow direction change angle by inserting short vertical elements between packing layers, as measured with air/water at ambient conditions. In comparison to standard bed configurations both dry and wet pressure drop are appreciably lower; however, the onset of loading occurs at a lower F factor. This is not surprising if we recognize that this configuration (Figure 7a) contains a doubled number of transitions between packing elements, that is, discontinuities in liquid flow where the liquid commences to accumulate and entrains partly due to the drag exhibited by the ascending gas.

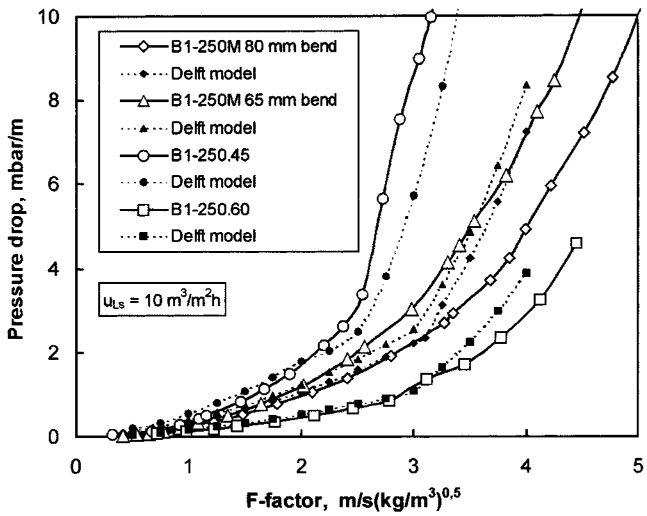

Figure 12. Pressure drop of Montz-pak B1-250M, with respectively shorter (65 mm) and longer (80 mm) bend (air/water, 1.013 bar, d = 0.6 m, $h_{pb} \approx$ 2 m).

More elegant and effective solution is to have the gas flow channels bent smoothly to the vertical in the bottom part of each corrugated sheet. Figure 12 compares the pressure drop of conventional 45° and 60° packings with the modified packing and indicates that a quite long bend (80 mm) is needed to achieve a significant capacity gain (more than 30%); however, still well below that of a 60° packing. Thin dotted lines show the respective predictions of the Delft method, which are astonishingly good in the preloading range. However, it should be noted that the loading point predictions correspond to a 0.9 factor of the values obtained with the original correlation.[6] The more conservative predictions are consistent with newer experimental evidence obtained with both air/water and total reflux systems.

Total reflux distillation performance of standard packings and modified packings with longer bends are compared in Figure 13. Again, very good agreement is found between predicted and measured pressure drop. Mass-transfer efficiency in the preloading range is reproduced very well by the original method, which, accidentally, overpredicts the observed curve precisely by the factor corresponding to the loss of efficiency observed in the preloading region.

The observed loss of efficiency in the preloading range, where the structured packing functions as a film flow device, may be attributed mainly to a substantial reduction in gas velocity corresponding to a much larger hydraulic diameter of the nearly vertical flow channels in the bottom part of the packing element. In addition, in this gas inlet section, which is one-third of the packing element height, there are no crossings of flow channels. Thus, the intensive interaction of crossing gas streams is partly eliminated, and this may be detri-

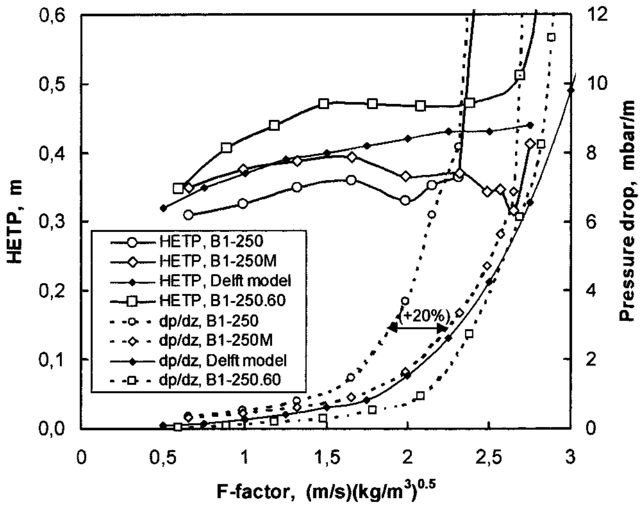

Figure 13. Total reflux distillation performance of Montz-pak B1-250M (cyclohexane/*n*-heptane, 1.03 bar, $d = 0.43$ m, $h_{pb} \approx 3.3$ m).

mental to efficiency in two ways. The rather strong interaction is responsible for thorough mixing of gas streams and consequently the equalization and maintenance of the driving force within a packing element/layer. On the other hand, it superimposes a swirling movement on the gas flow, that is, an increased effective gas velocity in each flow channel. Thus, both beneficial effects are partly lost. Furthermore, there may also be a detrimental effect on the liquid flow side. The absence of crossings of flow channels eliminates the possibility for mixing of liquid flowing along corrugation ridges, which appears to be a pronounced property of B1-type packings, responsible for a great extent and thoroughness of packing surface wetting within a packing element.

One should note that the efficiency of the modified packing improves significantly at higher F factors. Beyond the loading point (the range of practical interest) the efficiency is approximately equal to that of the standard packing. Most importantly, the point of the onset of flooding is shifted to a roughly 20% larger F factor, indicating the capacity increase potential in this case. Certainly, this is less than that observed in air/water experiments and may be attributed in part to the detrimental effect of a much lower surface tension as well as the fact that with total reflux an increasing F factor has a corresponding increase in liquid load. Because total reflux is the worst case from a hydraulics point of view, larger capacity gains can be expected in practice.

Concluding Remarks

The nature of pressure drop in a corrugated sheet structured packing has been revealed and manipulated accordingly. A monolith-like structure with much larger specific surface area allows capacity increases but is highly detrimental to efficiency. A significant improvement in capacity of a conventional corrugated sheet structured packing has been achieved: simply by bending smoothly to the vertical the corrugations in the lower third of each sheet. With respect to the performance of 60° packing, the capacity of the Montz M-packing is still wanting, indicating that considerable pressure drop due to gas–gas interaction also influences the capacity. The loss of efficiency in the preloading region remained within the design margin for conventional 45° packing. In the range of interest for application of this packing, the efficiency matches that of the original packing.

The Delft model proved to be versatile enough to account appropriately for all geometry manipulations considered in this study. Because it does not require any empirical, packing specific constants, it enables a tailor-made approach to the design and retrofitting of distillation columns containing corrugated sheet structured packings.

Acknowledgment

The authors are exceptionally grateful to Mr. Günther Frey, managing director of J. Montz GmbH, for all the support and encouragement through the years of the research effort summarized in this paper. We are also thankful to Mr. Marcel Behrens, presently a Ph.D. student at Delft, and to Dr. A. Frank Seibert, Dr. J. R. Fair, and the SRP staff for their contribution to this work.

Nomenclature

a_e = effective surface area, m^2/m^3
a_p = specific surface area of packing, m^2/m^3
b = corrugation base length, m
d = column diameter, m
d_{hG} = hydraulic diameter for the gas phase, m
$F_G = u_{Gs}(\rho_G)^{0.5}$ = gas load factor, m/s (kg/m^3)$^{0.5}$
$F_{G,lp}$ = loading point gas load factor, m/s (kg/m^3)$^{0.5}$
Fr_L = Froude number for liquid
g = gravity acceleration, m/s^2
HETP = height equivalent to a theoretical plate, m
h = corrugation height, m
h_{pb} = height of the packed bed, m
h_{pe} = height of the packing element, m
Re_L = Reynolds number for liquid
s = corrugation side length, m
u_{Gs} = superficial gas velocity, m/s
u_{Ls} = superficial liquid velocity, m/s
We_L = Weber number for liquid

Greek Letters

α = corrugation inclination angle, deg
α_{DC} = gas flow direction change angle, deg
α_{Le} = effective liquid flow angle, deg
β = crimp angle, deg
$\Delta p/\Delta z$ = pressure drop per unit length, mbar/m
δ = liquid film thickness, m
ϵ = packing porosity, m^3 voids/m^3 bed
φ = fraction of the triangular flow channel occupied by the liquid
μ_L = viscosity of liquid, Pa s
ρ_G = density of gas/vapor, kg/m^3
ρ_L = density of liquid, kg/m^3
σ = surface tension, N/m
Ω = fraction of packing surface area occupied by holes

Literature Cited

(1) Rocha, J. A.; Bravo, J. L.; Fair, J. R. Distillation columns containing structured packings: a comprehensive model for their performance. 1. Hydraulic models. *Ind. Eng. Chem. Res.* **1993**, *32*, 641; 2. Mass transfer model. *Ind. Eng. Chem. Res.* **1996**, *35*, 1660.

(2) Fitz, C. W.; Kunesh, J. G.; Shariat, A. Performance of structured packing in a commercial-scale column at pressures of 0.02–27.6 bar. *Ind. Eng. Chem. Res.* **1999**, *38*, 512.

(3) Fair, J. R. Personal communication, 1996.

(4) Olujic, Z.; de Graauw, J. Effect of geometrical features on pressure drop of corrugated sheet structured packings. Presented at the AIChE Annual Meeting, San Francisco, Nov 1994; paper 132F.

(5) Olujic, Z.; Seibert, A. F.; Fair, J. R. Influence of corrugation geometry on the performance of structured packings: An experimental study. *Chem. Eng. Process.* **2000**, *39*, 335.

(6) Verschoof, H.-J.; Olujic, Z.; Fair, J. R. A general correlation for predicting the loading point of corrugated sheet structured packings. *Ind. Eng. Chem. Res.* **1999**, *38*, 3663.

(7) Fair, J. R.; Seibert, A. F.; Behrens, M.; Saraber, P. P.; Olujic, Z. Structured packing performance—Experimental evaluation of two predictive models. *Ind. Eng. Chem. Res.* **2000**, *39*, 1788.

(8) Spiegel, L.; Knoche, M. Influence of hydraulic conditions on separation efficiency of Optiflow, *Chem. Eng. Res. Des./Trans. IchemE* **1999**, *77* (Part A), 609.

(9) Suess, Ph.; Spiegel, L. Hold-up of Mellapak structured packings. *Chem. Eng. Process.* **1992**, *31*, 119.

(10) Parkinson, G.; Ondrey, G. Packing towers. *Chem. Eng* **1999**, *106* (12), 39.

(11) Billingham, J. F.; Lockett, M. J. Development of a new generation of structured packings for distillation. *Chem. Eng. Res. Des./Trans. IchemE* **1999**, *77* (Part A), 583. See also: European Patent Application EP 0 858 830 A1, 19-08-1998—Bulletin 1998/34.

(12) Spiegel, L.; Meier, W. Structured Packings Today and Tomorrow. In *Proceedings of Vision 2020: Distillation Priorities Topical Symposium*, AIChE Spring Meeting, Atlanta, March 2000; p 102. See also: Sulzer Chemtech AG, Patent excerpt: 97-271914/24, 95-10-31 95GB-022086 (97-05-09) (WO 9716247-A).

(13) Olujic, Z. Development of a complete simulation model for predicting the hydraulic and separation performance of distillation columns equipped with structured packings. *Chem. Biochem. Eng. Q.* **1997**, *11*, 31.

(14) Olujic, Z. Effect of column diameter on pressure drop of a corrugated sheet structured packing. *Chem. Eng. Res. Des./Trans. IchemE* **1999**, *77* (Part A), 505.

(15) Onda, K.; Takeuchi, H.; Okumoto, Y. Mass transfer coefficients between gas and liquid phases in packed columns. *J. Chem. Eng. Jpn.* **1968**, *1*, 56.

(16) Spekuljak, Z.; Billet, R. Mass transfer in regular packing, *Rev. Latinoam. Transferencia Calor. Mater.* **1988**, *11*, 63.

(17) Zogg, M. Stoffaustausch in der Sulzer-Gewebepackung. *Chem.-Ing.-Techn.* **1973**, *45*, 67.

(18) Stoter, C. F. Modelling of Maldistribution in Structured Packings, D.Sc. Dissertation, Delft University of Technology, Delft, The Netherlands, 1993.

(19) Woerlee, G. F. Hydrodynamics and Mass Transfer in Packed Columns and their Application for Supercritical Separations, D.Sc. Dissertation, Delft University of Technology, Delft, The Netherlands, 1997.

(20) Woerlee, G. F. Structured packing for mass and/or heat exchange between a liquid and a gas, and .... Dutch Patent Office, Application No. OA 1005990, May 6, 1997.

(21) Zich, E.; Jansen, H.; Leben, J.; Rietfort, T.; Zelmer, J.; Kaibel, B. Packung fuer Waerme- und Stoffaustauschkolonnen. Deutsches Patent- und Markenamt, Offenlegungsschrift. DE 100 01 694 A 1, 2000.

(22) Kaibel, G.; Rheude, U.; Stroezel, M.; de Graauw, J.; Olujic, Z.; Frey, G.; Jansen, H. Packing for mass transfer columns. European Patent EP 0 785 019 B1, 1997.

Received for review April 12, 2001
Revised manuscript received September 20, 2001
Accepted September 21, 2001

IE010323J