Performance Characteristics of a Monolith-like Structured Packing*

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In memoriam Prof. Emeritus Vera Johanides

In recent years, the monolith, in the meantime widespread in automotive applications as exhaust gas converter, has emerged as an efficient, low-pressure drop phase contacting device. More demanding, heterogeneous catalysis applications are now being investigated. In general, a structure, which brings reactants efficiently into contact with the solid catalyst under co- and counter current conditions, should be considered also suitable for common mass transfer operations, such as distillation.

This paper describes results of a combined experimental and modelling effort undertaken to evaluate the hydraulic and mass transfer characteristics of monolithic structured packings. By inserting flat sheets between corrugated sheets the open channel packing geometry was transformed into a monolith-like structure with a multiplicity of closed inclined triangular channels. In this way the specific surface area was increased considerably. Although against common sense on first sight, the increase in surface area led to a significant reduction in pressure drop, accompanied by an appreciable capacity increase with respect to that of the original packing. However, closed channel structure proved to be very detrimental to mass transfer efficiency. This experience has led to conclusion that monolith structures with inclined channels are not suitable for counter-current gas/liquid contacting operations.

Keywords:
Monolith, structured packing, capacity, mass transfer efficiency, distillation, pressure drop

Introduction

Typical chemical process plants are designed to carry out desired chemical and physical changes of feed material. In the equipment used for these purposes two or more phases are brought into intimate contact. In a majority of industrial applications, mixtures of gases and liquids are brought in contact using inert solid as a carrier for liquid phase to enable a smooth counter-current operation, and provide surface area necessary for creating the interfacial area.

In comparison to conventional gas/liquid contacting devices employed in distillation, the corrugated sheet structured packings, characterised by an ordered, highly open structure allow operation at lowest pressure drop per theoretical plate (equilibrium stage). This property led to considerable capital savings particularly in vacuum and near atmospheric distillation applications. Replacing trays by structured packings enabled often very large capacity increase at lowest investment cost and in case of new designs similar gains came from significantly reduced column dimensions. However, with time, structured packings became an established technology and soon the ever-growing need for bulk chemicals and a general reluctance for large capital investments created a new push toward old goal, namely to get more out of existing equipment. During the last decade, this by increased market competition imposed pressure, forced packing manufacturers and users to search for improvements in design of structured packing that will allow more capacity and/or efficiency.

The essence of process equipment engineering is represented graphically in Fig. 1, as a triangle indicating the relation between efficiency and capacity, two key design and operating parameters, and the cost of manufacture[1]. Obviously an equipment designer would like to maximize, both efficiency and capacity, while minimizing the costs of manufacture.

Unfortunately, as illustrated in Fig. 2, capacity and efficiency are interrelated, i.e. counteract each other in practice to the extent depending strongly on the type of the device used to provide phase contact[2,3]. This implies often making necessary trade-offs between capacity and efficiency while keeping

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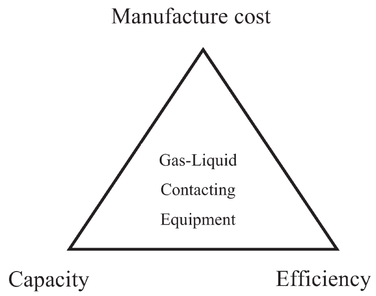


Fig. 1 – *Relationship between capacity, efficiency and the cost of manufacture of gas/ liquid contacting devices*

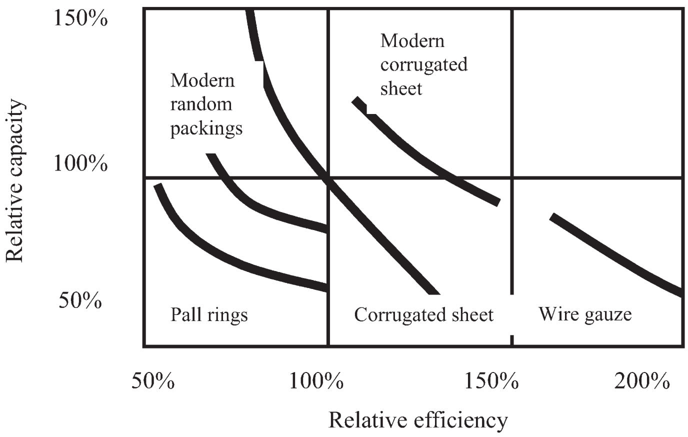


Fig. 2 – *Schematic illustration of the capacity/efficiency interrelation for various packings employed in distillation (Reproduced from: Stichlmair, J., Fair, J. R., Distillation Principles and Practice, McGraw--Hill, New York, 1998)*

the costs low enough to remain competitive in the hard market race. Breaking through these relationships is difficult, and represents a hard challenge equipment manufacturers face from time to time.

In general, the designers of process equipment for contacting gas and liquid phases strive for compact, efficient devices. During the last few decades, the goal was to arrive at a highly ordered (regular) structure which should intrinsically enable a scale-up less risky than that which is generally experienced with random packings. In distillation technology a real breakthrough was made by introduction of corrugated sheet structured packing some 20 years ago. In reaction engineering, the continuous efforts to reduce considerably pressure drop involved with low porosity beds particularly those employed in fixed bed/trickle flow reactors, led to the development of so called monolithic catalysts/reactors.

According to *Humphrey* and *Keller*[3], the monolith is a structure composed of individual parts, which together form an organised whole, comprising a multiplicity of narrow, closed channels, characterised by a high mechanical strength, high surface-to-volume ratios and most importantly low pressure drop. In fact, the name monolith is adopted only in the reaction-engineering field, for a class of compact ceramic bodies comprising a multiplicity of parallel, vertically oriented, very narrow channels, with various forms of internal wall geometry. A comprehensive overview of the state of the art and prospective industrial applications of these so-called classical monoliths can be found in a recent paper from the industrial catalysis group of the TU Delft[4]. It should be noted that a relatively good ratio of pressure drop and capacity is obtained only in co-current operation. Nevertheless, the authors appeared to be very enthusiastic about possible benefits from the use of monoliths in counter-current gas/liquid operations such as distillation.

The objective of this paper is to present and discuss the results of a comprehensive experimental and modelling effort devoted to the evaluation of the potential for capacity increase of conventional structured packing by adopting a monolith-like, closed inclined channel structure. Indeed, one of such structures enabled capacity increase but failed heavily on mass transfer side.

Background

Introduction of the high surface area, low-pressure drop corrugated sheet packing made of rather expensive metal gauze, by Sulzer in mid 1960s, may be considered as a milestone in the development of distillation equipment. Next one, introduction of Sulzer corrugated sheet metal packing Mellapak in late 1970s, represented a real breakthrough, and a number of packing manufacturers followed. Thanks to a superb efficiency and capacity, this much cheaper type of corrugated sheet metal structured packing found a wide application in industrial practice, mainly in conjunction with distillation. Low pressure drop per theoretical plate proved to be of a particularly big advantage in vacuum and near atmospheric distillations, however, a good mass transfer performance proved to be possible only in conjunction with a uniform initial liquid distribution. Some bad experiences in practice indicated that expected performance of structured packing couldn't be achieved/maintained in distillations performed under higher operating pressures[5–7], such as employed in the manufacture of important bulk chemicals (ethene, propene, iso-butane, etc.). This still not quite explained, poor performances of structured packing have clearly demonstrated a worrying lack of understanding the relation between the hydraulics and mass transfer performance of this rather simple contacting device. However, the failure of structured packing to perform accordingly gave a strong impulse to tray developments. The effort undertaken during the last decade by major tray manufacturers and some users resulted in the development of a number of so called high capacity trays[8].

Figure 3 shows the phases in assembling a structured packing element equipped with wall-wipers to avoid excessive wall flow of liquid. By rotating each subsequent element to each other by 90 degrees large scale mixing of both phases is enabled. The mixing of gas and liquid occurs also within one packing element, however only in parallel to sheets and to an extent depending on the design of packing surface and corrugations.

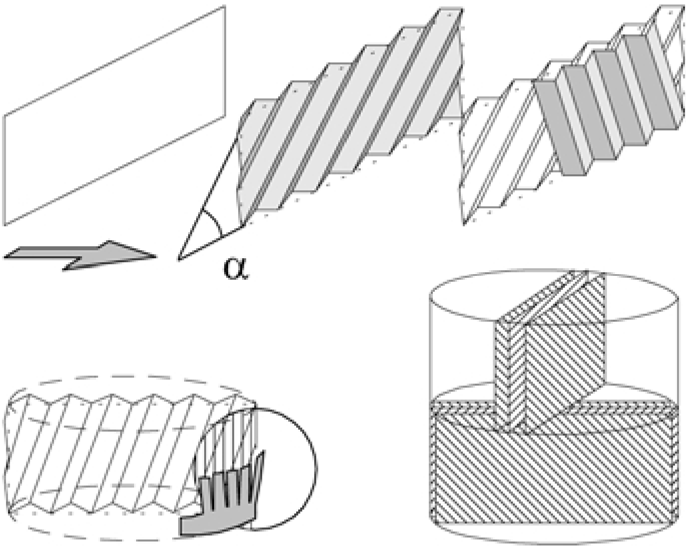


Fig. 3 – *Schematic illustration of assemblage/installation of a corrugated sheet structured packing.*

As established in our packing hydraulics studies, and taken into account accordingly in the Delft model[9,10], the pressure loss as experienced in a structured packing bed comprises three major components: gas-liquid interaction on the surface of liquid film covering packing surface, losses related to abrupt direction change at transition between packing element/layers, and losses due to interaction of gas streams at the gas-gas interfaces created at open crossings of gas flow channels. The later one, much less obvious than other two, appeared to be responsible to a greater part for pressure loss of conventional 45 degrees packing. According to *Stoter* et al.[11], it is responsible for mixing of crossing gas streams and consequently for lateral equalization of concentration profile, i.e. maintaining the driving force for mass transfer within a packing element. However, there is no evidence on direct contribution to mass transfer process at gas/liquid interface. Therefore, it could be expected that the performance of corrugated sheet structured packing should eventually be improved if one find the way to maximize the ratio of "useful" frictional pressure drop to "useless" pressure drop due to gas/gas interaction.

An evident approach seems through elimination of the interaction of crossing gas streams by inserting (sandwiching) flat sheets between corrugated sheets. In this way the structure of a common corrugated sheet packing is transformed into a monolith-like structure with a multiplicity of short inclined flow channels, but with respect to common monoliths with a much larger hydraulic diameter.

Geometrical features of a monolith-like structured packing

Figure 4 shows a side view and a top view of monolith-like modification of a corrugated sheet structured packing. The inserted flat sheet creates two closed triangular flow channels, however, according to the expression (1), the hydraulic diameter for gas flow in dry packing is the same for common and monolith-like packing.

$$d_{\mathrm{hG,dry}} = \frac{2bh}{b+2s} \tag{1}$$

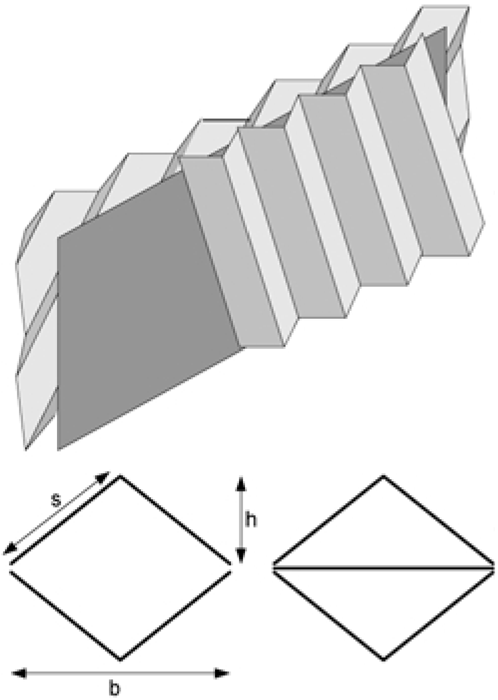
where b/m is the corrugation base length, h/m the corrugation height, and s/m the corrugation side length. The later one follows from:

$$s = \sqrt{\left(\frac{b}{2}\right)^2 + h^2} \tag{2}$$

V-shaped fraction of triangular gas flow channel occupied by corrugation sides (walls) is

$$\varphi = \frac{2s}{2s+b} \tag{3}$$

By placing flat sheet in between corrugated sheets (see Figure 4), φ = 1, the installed specific surface area will increase substantially. Consequently, the frictional pressure drop will increase proportionally to the increase in surface area. However, in absolute numbers, this increase is roughly only one half of the saving due to the elimination of gas/gas interaction, which implies that total pressure drop would be lower than that of the original packing. If wetted, i.e. covered completely by a flowing film, such a large surface area should enable a substantial increase in mass transfer efficiency. In other words, with this rather simple transformation of common structured packing into monolith-like packing it appears possible to reach two objectives in one move, a considerable reduction of total pressure drop and a significant increase of the mass transfer efficiency.



F i g . 4 – *Side and top view of basic segment of a monolith-like structured packing, with illustration of characteristic dimensions of corrugated sheets.*

Delft model predictions

With respect to first published version[9,10], the method used in this study contains new, generally valid correlations for determination of loading point and the effect of loading on pressure drop[12], which take into account the effects of corrugation angle and packing size accordingly. Knowing the loading point is essential for column designers, and the shift in the loading point gas load represents an indication for corresponding capacity variations. A complete overview of working equations of the Delft model can be found elsewhere[13].

In order to get an indication of achievable gains in capacity and/or efficiency the Delft model was adapted accordingly. Namely the gas-gas interaction coefficient in the overall pressure drop equation was set equal to zero, and the factor describing the fraction of the channel walls in contact with gas flow was set to the value 1.

Dimensions of a standard corrugated sheet and its modification into monolith-like packing are shown in Table 1 together with predicted values of pressure drop, mass transfer efficiency (HETP) and the loading point gas load. Since it was assumed that the complete installed surface area is actively wetted, the model predictions shown in Table 1 indicate the theoretical limits for the performance improvement in this case. A more than halved HETP value in case of monolith-like packing is the consequence of the fact, that in addition to the efficiency enhancement proportional to surface area increase there is also a significant mass transfer enhancement due to a substantial increase in the gas phase Sherwood number. The later one due to the fact that now (φ = 1) all three sides of triangular gas flow channel are involved in mass transfer process.

It is striking the extent of reduction in total pressure drop. As suggested earlier, it is equivalent to the gain resulting from the fact that with inserting a flat sheet between two corrugated sheets the energy consuming gas-gas interaction has been replaced with less energy consuming gas-liquid friction. Although monolith-like packing produced less pressure drop than standard packing, there is no difference in the value of the loading point gas load. This is simply because of the same value of the hydraulic diameter for the gas ($\approx$ 0.011 m), which is the characteristic geometry parameter in the loading point correlation.

Obviously, the above-predicted performance represents an ideal situation. Certainly, in a bed comprising packing elements with flat sheets inserted between corrugated sheets there will be no mixing of crossing liquid and vapour streams within a packing element. The ability of liquid to flow over the corrugation ridges and to flow partly to adjacent sheet, via the crossing points proved to be essential for the extent and thoroughness of lateral spreading of liquid in case of Montz-pak B1–250, which is taken as base case packing in this study. In other words a completely different wetting behaviour can be expected from a monolith-like version of the same packing.

T a b l e 1 – *Comparison of predicted performances of standard and monolithic packings (cyclohexane/heptane, 1.03 bar, d = 0.43 m, h_{pb} ≈ 3.3 m, F_G = 1.5 m s^{-1} (kg m^{-3})$^{0.5}$)*

Packing version	a_p / m^2 m^{-3}	h / m	b / m	φ / –	HETP / m	$\Delta p/\Delta z$ / mbar m^{-1}	$F_{G,lp}$ / m s^{-1} (kg m^{-3})$^{0.5}$
Standard	250	0.0113	0.0226	0.5861	0.39	0.89	1.89
Monolithic	398	0.0113	0.0226	1	0.17	0.59	1.89

The uncertainties around possible effects of closed channel structure could be answered properly only by an experiment. A number of options regarding the size and location of flat sheets have been evaluated in a series of hydraulic tests. This finally led to a configuration, which has been exposed to a total reflux test.

Experimental method

Figure 5 shows the scheme of the packing hydraulics' simulator used in this study. The internal diameter of the column made of plexiglas is 0.45 m. Packed heights employed in this study were 0.8 m and 2.2 m, respectively. Shorter bed refers to monolith-like packing. All runs were carried out with air-water system at room temperature and atmospheric pressure. Water followed a closed circuit. It was drawn from the liquid tank and pumped through the flowmeters up to the distributor, from which it flowed over the packing back into the tank. Liquid distributor was a large turndown narrow trough distributor with drip pipes arranged concentrically and ending about 2 cm above the top of the packing. The drip pipe (point) density was 100 per m^2 (10 at the periphery and 6 in the center). Liquid loads employed were up to 40 $m^3\ m^{-2}\ h^{-1}$. Air was taken from the surrounding and supplied to the column from a blower and metered by a calibrated anemometer.

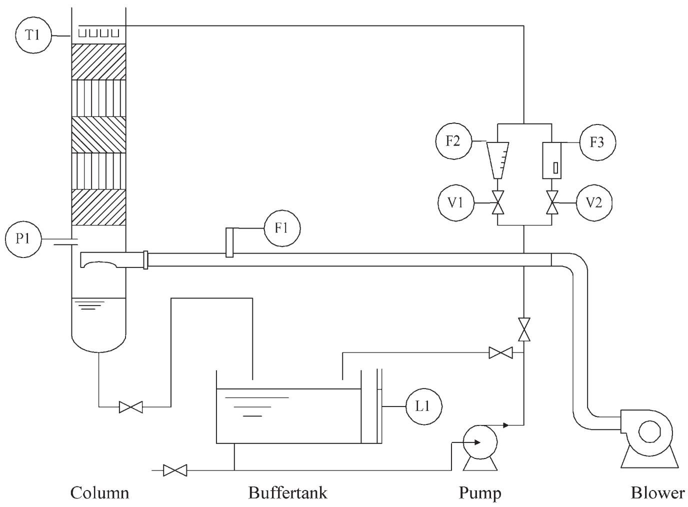


Fig. 5 – *Schematic of 0.45 m ID packed column hydraulics simulator at TU Delft*

Pressure drop gradient was measured over the test section using a U-tube manometer filled with water. Tests begun by pumping the liquid over the packing at highest rate for some time to ensure a thorough wetting of packing. After this preparation the liquid was set to a desired flow rate and the airflow was increased in steps up to the maximum flow while readings were taken of air flow rate, pressure drop, liquid level in the supply tank, and column temperature. Dynamic liquid holdup was obtained by recording accurately the liquid level in the water supply tank, taking into account an average static holdup as well as corresponding empty column holdup values both measured in a separate experiment.

Total reflux distillation experiments were carried out at Separations Research Program at the University of Texas at Austin, in a column with an internal diameter of 0.43 m. In all cases the packed height was around 3.3 m. The cyclohexane/heptane system was used. The operating pressure was varied from 0.33 to 4.14 bar, to determine the effect of physical properties. A detailed description of the experimental set-up and procedure employed at SRP can be found elsewhere[14].

As mentioned before the Montz-pak B1–250, an unperforated packing with shallow embossed surface and the standard corrugation angle of 45 degrees, is used as the base case packing. All modifications were made using this packing in conjunction with flat sheets made from the same shallow embossed material, used to make the corrugated sheets. In the before mentioned simulation effort the size of sandwiched flat sheets was assumed to be equal to the size of neighbouring corrugated sheets. Knowing that this may cause liquid build-up and drainage problems at the transitions between packing layers and in the wall zone, the prototype packing has been provided with accordingly dimensioned and positioned flat sheets[15]. Figure 6 shows schematically the configurations tested in this study. First one denoted B1–250ED is the one with the inserted flat sheets reaching the bottom part packing element, and the other one (B1–250EU) has flat sheets levelled with the top side of a packing element. Main dimensions of common and monolithic structures tested are summarised in Table 2.

Table 2 – *Dimensions of standard and monolithic packings tested in this study*

Packing version	a_p $m^2\ m^{-3}$	h m	b m	s m	h_{pe} m	ε –
B1–250	244	0.0120	0.0225	0.0164	0.197	0.98
B1–250ED/EU	329	0.0120	0.0225	0.0164	0.197	0.97

In what follows the most important performance characteristics, pressure drop, holdup, and mass transfer efficiency are plotted against the F-factor (gas/vapour load, the product of superficial vapour velocity and the square root of the vapour density) with liquid load or operating pressure as a parameter.

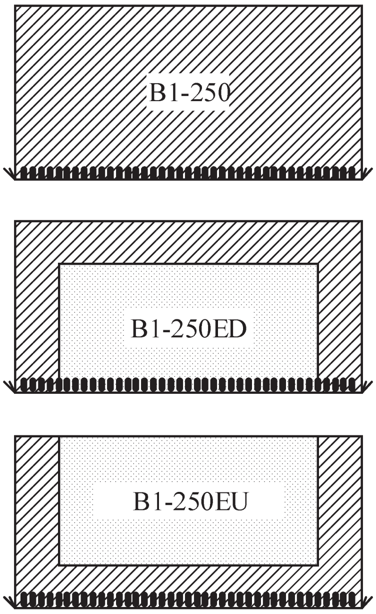


Fig. 6 – *Schematic illustration of packing configurations tested in this study*

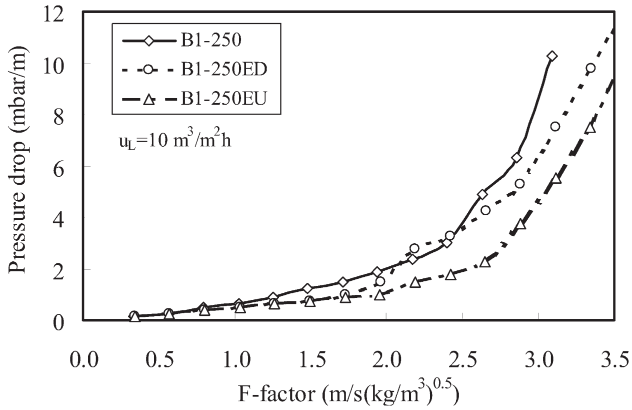


Fig. 7a – *Comparison of measured pressure drops for a liquid load of 10 m^3 m^{-2} h^{-1} (air/water, 1.013 bar, d = 0.45 m)*

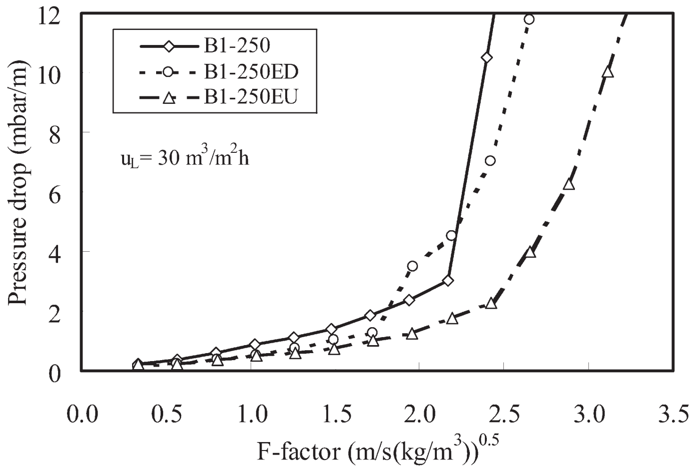


Fig. 7b – *Comparison of measured pressure drops for a liquid load of 30 m^3 m^{-2} h^{-1} (air/water, 1.013 bar, d = 0.45 m)*

Results and discussion

Figures 7a and b show the effect of gas load on pressure drop of the common and two monolithic structures at a moderate and a high liquid load, respectively, as measured using air/water system at ambient conditions in a column with an internal diameter of 0.45 m. Although with approximately 45 % larger surface area, both modifications produced a considerably lower pressure drop than the standard packing in the preloading region. Strikingly, the onset of loading appeared to be dependent on the positioning of flat sheets. The configuration with flat sheets in the bottom part of the packing element appeared to load much earlier than standard one and the upside-down configuration (B1–250EU). This observation was of particular importance, because it clearly indicated the bottom part of a packing element as a bottleneck for transition of phases between packing elements. This is in agreement with observations reported by Suess and Spiegel[16]. Their experimental evidence on liquid holdup distribution in the loading range in a 1 m diameter bed, obtained utilising gamma ray technique, provided basis for a capacity increasing packing modification[17], which finally opened the road for introduction of new generation of high capacity packings[18,19].

The configuration with flat sheets in the upper part reached the pressure drop of 2 mbar m^{-1} at a 30% higher value of F-factor than the standard one, which indicates that this modification allows operation at correspondingly larger capacity. This gain in capacity is substantial and would justify manufacture of new packing if it would be possible in practice with organic liquids. Namely, from experience it is known that because of much higher surface tension a packing provides an incrementally higher capacity with air/water than with an organic liquid system. As indicated in Figure 8, showing the comparison of mean dynamic liquid holdups of standard and the monolith like packing, a rather low-pressure drop of monolithic packing can be attributed to a significantly lower liquid holdup. From the trend in the holdup curves, it becomes obvious that the monolith-like packing can stand higher gas load without causing liquid build-up at transitions of packing elements, and this makes operation at a relatively higher capacity possible. On the other hand, this low operating holdup indicated indirectly that a certain degree of efficiency loss might be expected from the monolithic packing. It turned to be even worse, as it may be conjectured from results of total reflux experiments shown in following plots.

Figure 9 shows total reflux performance data for monolith-like packing at three operating pressures. As might be expected efficiency improves

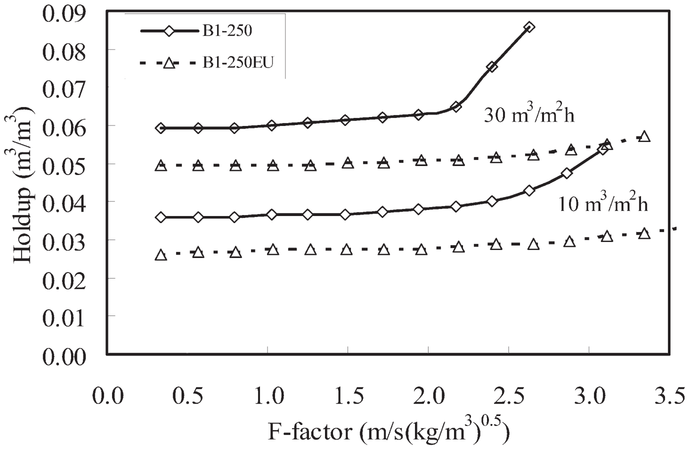


Fig. 8 – *Comparison of measured liquid hold-ups of standard and monolith-like packing, at two characteristic liquid loads (air/water, 1.013 bar, d = 0.45 m)*

with increasing operating pressure at the expense of decreased capacity. In this respect the monolithic packing behaves similarly to other packings tested under total reflux conditions. However, the effect of operating pressure is much more pronounced and generally the efficiency curves indicate a rather poor efficiency in the preloading range. As illustrated in Figure 10, this is opposite from the trend observed with common packing. On the other hand, the efficiency of monolith-like packing improves strongly with increasing F-factor, and upon reaching the loading range, it reaches to the level of efficiency observed with common type packing.

The reason for such a poor efficiency in the preloading region was certainly the liquid maldistribution. First of all, because of the closed channel structure in the upper part of packing element the first packing element is not functioning as a liquid redistribution element. Only few of the channels get the liquid, which means that a considerable number of channels are not actively involved in mass transfer process. At lowest gas load the initial maldistribution pattern propagates downward bed resulting in a very poor performance. Namely, due to presence of a flat sheet between two corrugated sheets the strongly pronounced mixing of liquid at crossings of corrugated sheets, as observed with standard packing, is completely avoided and therefore there is no lateral spreading of liquid within a packing element, and the surface used is equivalent to that covered by liquid rivulets. With increasing pressure of upwardly flowing gas, the liquid builds-up at transitions between packing elements and is forced to spread laterally. In this way, with increasing gas load, more and more channels get the liquid, and the fraction of surface area involved in mass transfer increases. This trend is more pronounced with increasing operating pressure, i.e. correspondingly increasing liquid load. However, in all cases, the best performance reached in loading region is not better than that of standard packing, indicating that even under good wetting conditions the extra installed surface area is not fully used.

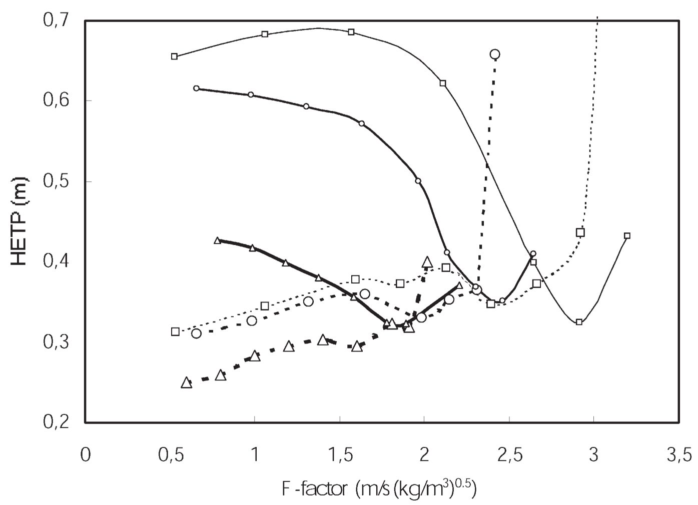


Fig. 10 – *Comparison of mass transfer efficiencies measured under total reflux conditions with operating pressure as a parameter (cyclohexane/n-heptane, d = 0.43 m). For symbols see Figure 11*

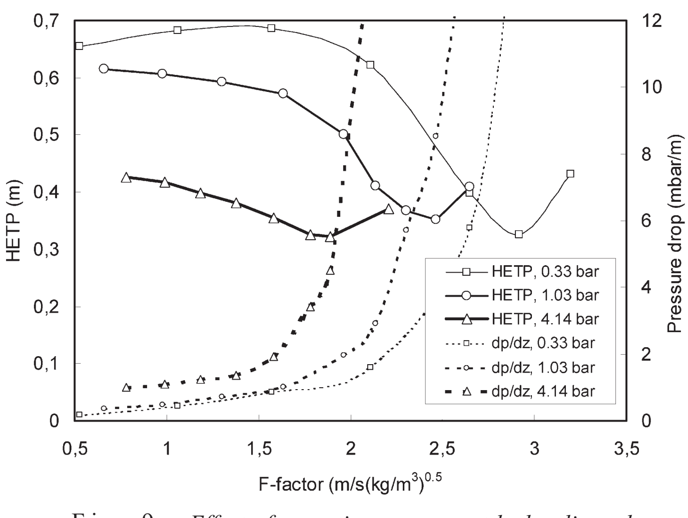


Fig. 9 – *Effect of operating pressure at hydraulic and mass transfer performance of monolith-like packing under total reflux conditions (cyclohexane/n-heptane, d = 0.43 m)*

The fact that the performance reached in preloading region is well below that of standard packing indicates, that not only vertically oriented flat sheets, but also inclined corrugations are not wetted accordingly. The liquid cannot leave or enter a closed channel within a packing element and tends to form rivulets along the lowest edge of the triangular channel. This indirectly indicates how important, for surface wetting and renewal within a packing element, is the open communication between crossing sheets. On the other hand with increasing gas load, the spreading of liquid over the corrugation ridges of standard packing is suppressed, which explains the deteriorating trend in efficiency of standard packing. Upon reaching the point of onset of loading regime the efficiency improves strongly, however this trend is limited to a narrow range and ends upon reaching the point of onset of flooding.

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. Certainly, as indicated in Figure 11, showing the cyclohexane/heptane data, the gain in capacity is less pronounced than that observed with air/water system. However it is still significant, and, strikingly, it increases with increasing pressure. It should be noted that in a total reflux experiment the liquid load increases proportionally to F-factor as well as to the increase in operating pressure. At an F-factor of 1.5 m s^{-1} (kg $m^{-3})^{0.5}$, the corresponding liquid loads for operating pressures of 0.33, 1.03, and 4.14 bar are (rounded) 16, 21, and 35 m^3 m^{-2} h^{-1}, respectively. This indicates indirectly that monolithic structure can handle hydraulically the liquid loads encountered in typical high-pressure distillation applications.

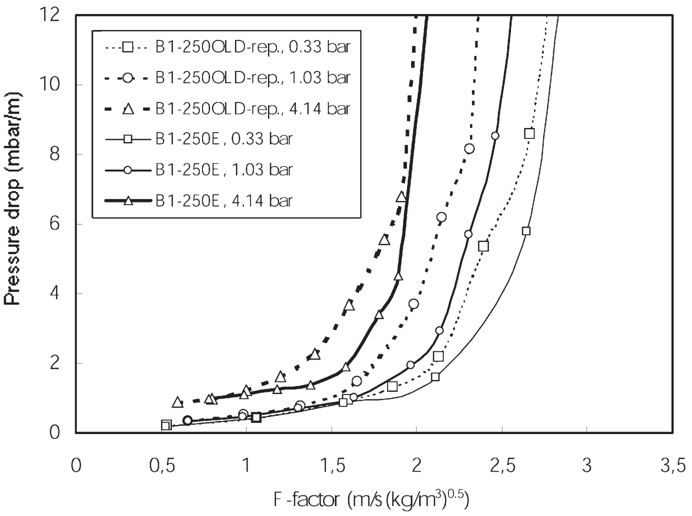


Fig. 11 – *Comparison of pressure drop of standard and monolithic packings measured under total reflux conditions with operating pressure as a parameter (cyclohexane/n-heptane, d = 0.43 m). "Old-rep." Refers to the new set of data (repeated test) obtained with B1–250 packing (see ref. 14 for original test)*

Figure 12 illustrates the predictive accuracy of the Delft model with respect to the pressure drop. The characteristic geometry of monolithic packing (B1–250EU) containing a relatively small fraction of open channels, has been accounted for by simply adjusting, accordingly, the parameter (φ = 0.85) which stands for the fraction of a triangular gas flow channel exposed to the friction and to the gas/gas interaction, respectively. Since flat sheets do not cover roughly 15 % of the packing element height, it was assumed that contribution of gas/gas interaction will be equivalent to this fraction, and the contribution of gas/liquid interaction will be increased accordingly. As shown in Figure 12, with such a simple model modification an astonishingly good agreement has been achieved between prediction and experiment in both total reflux and air/water cases. Only, at high liquid (water) load the loading point is under-predicted, which may be attributed to the fact that liquid load effect is obviously much less pronounced with monolithic packing than with standard packing, for which the loading point correlation[12] was developed.

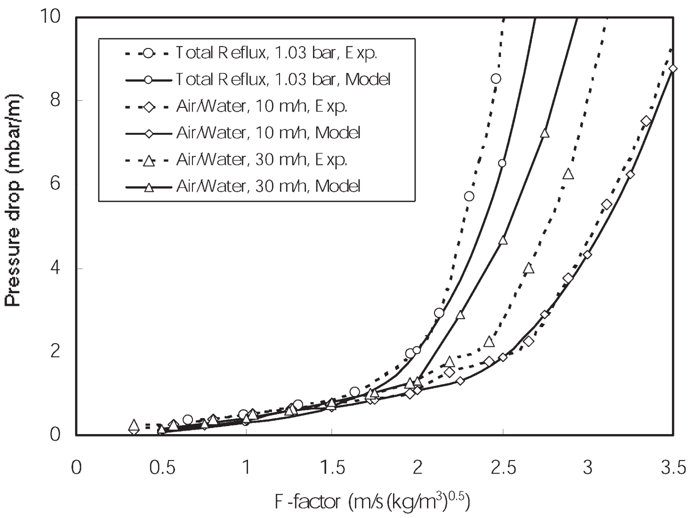


Fig. 12 – *Predicted versus measured pressure drop of monolithic packing, with illustration of liquid load effect (total reflux, cyclohexane/n-heptane,1.03 bar; air/water, 1.013 bar, u_{Ls} = 10 and 30 m^3 m^{-2} h^{-1})*

Conclusions

The potential for capacity increase of corrugated sheet structured packings by adopting a monolith-like structure has been evaluated experimentally. "Useless" pressure drop due to interaction of crossing gas streams has been largely replaced by less pronounced "useful" frictional pressure drop by introducing a flat sheet between corrugated sheets. The monolith-like structure with much larger specific surface area produced a lower pressure drop, and consequently allowed a substantial capacity increase. However it appeared to be prone to development of severe liquid maldistribution, which, particularly in preloading region appeared to be highly detrimental to efficiency.

Because of the inclination of closed channels, the liquid tends to flow in rivulet form along the base of channel formed between corrugations and the flat plate, which implies a significant loss of effective surface area, and a reduced residence time for liquid. Because of this, even relatively short monoliths with inclined channels are generally less suitable for a counter-current operation than common ones.

Delft model proved to be capable of predicting the effects of packing modification on the pressure drop. However, on mass transfer side, there are no provisions in the model, which could take into account the drastic changes in surface wetting behaviour as experienced in case of monolithic structures.

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Nomenclature

a_p – specific surface area, m^2 m^{-3}
b – corrugation base length, m
d – column diameter, m
d_{hG} – hydraulic diameter for the gas, m
dp/dz – pressure drop per unit length, mbar/m
$F_G = u_G\ (\rho_G)^{0.5}$ – gas load factor, m s^{-1} (kg m^{-3})$^{0.5}$
$F_{G,lp}$ – loading point gas load factor, m s^{-1} (kg m^{-3})$^{0.5}$
$HETP$ – 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
s – corrugation side length, m
u_G – superficial gas velocity, m s^{-1}
u_L – superficial liquid velocity, m h^{-1} or m^3 m^{-2} h^{-1}

Greek letters

α – corrugation inclination angle, °
ε – packing void fraction (porosity), m^3 m^{-3}
φ – fraction of the triangular flow channel occupied by liquid, –
ρ_G – density of gas, kg m^{-3}

References

1. *Olujic, Z.*, Performance Modelling of Distillation Internals: Comprehensive Approaches for Rigorous Design of Structured Packing Columns, in Kunesh, J. G., and Krishnamurthy, K. (Ed.), Proceedings of the Vision 2020 Distillation Priorities Topical Symposium, Publ. No. 129, pp. 166–179, AIChE Spring National Meeting, Atlanta, March 5–9, 2000.
2. *Stichlmair, J., Fair, J. R.*, Distillation Principles and Practice, McGraw-Hill, New York, 1998.
3. *Humphrey, J.L., Keller II, G.E.*, Separation Process Technology, McGraw Hill, New York, 1997.
4. *Kapteijn, F., Heiszwolf, J. J., Nijhuis, T. A., Moulijn, J. A.*, Monoliths in Multiphase Catalytic Processes – Aspects and prospects, CATTECH **3** (1999) 1, 24.
5. *Fitz, C. W.; Kunesh, J. G.; Shariat, A.*, Ind. Eng. Chem. Res. **38** (1999) 512.
6. *Nooijen, J. L., Kusters, K. A. , Pek, J. J. B.*, The Performance of Packing in High Pressure Distillation, ICHEME Symp. Ser. **142** (1997) 885.
7. *Zuiderweg, F. J., Olujic, Z., Kunesh, J. G.*, Liquid Backmixing in Structured Packing in High Pressure Distillation, ICHEME Symp. Ser. **142** (1997) 865.
8. *Bravo, J. L., Kusters, K.*, Tray Technology for the New Millennium, in Kunesh, J. G., and Krishnamurthy, K. (Ed.), Proceedings of the Vision 2020 Distillation Priorities Topical Symposium, Publ. No. 129, pp. 85–101, AIChE Spring National Meeting, Atlanta, March 5–9, 2000.
9. *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.* **11** (1997) 31.
10. *Olujic, Z.* Effect of Column Diameter on Pressure Drop of a Corrugated Sheet Structured Packing. *Chem. Eng. Res. Des. – Trans. Inst. Chem. Eng.* **77** (1999) Part A, 505.
11. *Stoter, C. F., Olujic, Z., de Graauw, J.*, Chem. Eng. J. **53** (1993) 55.
12. *Verschoof, H.-J., Olujic, Z., Fair, J. R.* Ind. Eng. Chem. Res. **38** (1999) 3663.
13. *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. **39** (2000) 1788.
14. *Olujic, Z., Seibert, A. F., Fair, J. R.*, Influence of Corrugation Geometry on the Performance of Structured Packings: An Experimental Study, Chem. Eng. and Processing **39** (2000) 335.
15. *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, 31-05-2000.
16. *Suess, Ph., Spiegel, L.*, Chem. Eng. and Processing **31**, (1992) 119.
17. *Billingham, J. F., Lockett, M. J.*, Development of a New Generation of Structured Packings for Distillation, *Trans. Inst. Chem. Eng.* **77** (1999) Part A, 583. See also: *European Patent Application* EP 0 858 830 A1, 19-08-1998 – Bulletin 1998/34.
18. *Parkinson, G., Ondrey, G.,* Chemical Engineering **106** (1999) No. 12, 39.
19. *Olujic, Z., Jansen, H., Kaibel, B., Rietfort, T., Zich, E.,* Stretching the Capacity of Structured Packings, Paper presented in the Distillation Honors Session (J.R. Fair) at the AIChE Annual Meeting, Los Angeles, Nov. 14, 2000.