Packed Columns for Absorption Process

An Economic analysis

by Elisabetta Brunazzi, Giuliano Nardini, Alessandro Paglianti

In the last few years an increasing number of restrictions have been introduced to limit pollutant emissions into the environment and, on the other hand, industry requires internals that reduce both operating costs and dimensions of absorption columns.
In the present work an economic analysis on column packings has been performed. The results show that structured packings can save energy and significantly reduce the operating and investment costs by offering reduced values of pressure drops per theoretical stage in comparison to conventional dumped packing.

The necessity to reduce the concentration of pollutants from a gas stream or to increase the recovery efficiency in a synthesis production unit has led to an accurate re-examination of absorption processes and equipment internals.
Particular attention has been dedicated to develop packings that allow both increasing absorption efficiency and reduced pressure drops.
Parkinson and Ondrey [1] have recently presented an analysis and review of different packings for absorption towers marketed by manufacturers. In their analysis they report on the interesting performances of some common and well known structured packings (e.g. Flexipac, made by Koch-Glitsch and Mellapak, made by Sulzer Chemtech) as well as that of a novel type of structured packing, the HelieR by Polcon Italiana Srl, made by elements with helical geometry (see Figure 1).
This is said to reduce flooding and increase capacity by as much as 20 to 30% over conventional structured packings. The cost per cubic meter of regular type packings is higher than the cost for common random packings. However, it is well known that regular packings offer lower pressure drops per theoretical stage, thus reducing energy consumption and hence operating costs. In addition, Parkinson and Ondrey [1] also explained that structured packings are favoured over less-expensive random packings because they allow a more predictable scale-up of a column.
Notwithstanding these positive characteristics, while it is possible to find many systematic studies on random packings, only few reports on structured packings have been published so far in open literature. The lack of experimental data is probably due to the fact that suppliers tend to preserve proprietary know-how and, as a consequence, accurate design can be often difficult.
In addition, while some data obtained in large columns are available for the common structured packing types (e.g. Flexipac, Mellapak, Montz), to our knowledge, experimental data

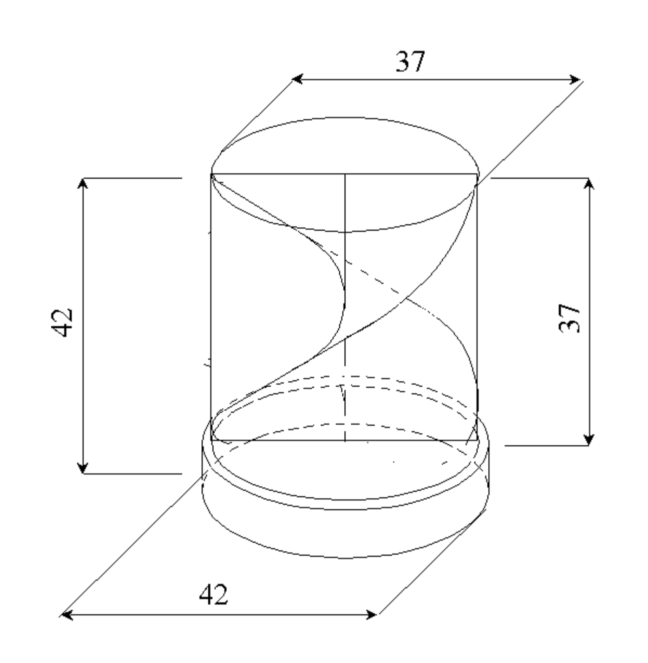

Figure 1 - Schematic drawing of the HelieR element

E. Brunazzi, A. Paglianti, Dip. di Ingegneria Chimica, Chimica Industriale e Scienza dei Materiali - Università degli Studi di Pisa - 56126 Pisa - e.brunazzi@ing.unipi.it - paglianti@ing.unipi.it.
G. Nardini, Consorzio Polo Tecnologico Magona - 57023 Cecina (LI) - nardini@polomagona.it.

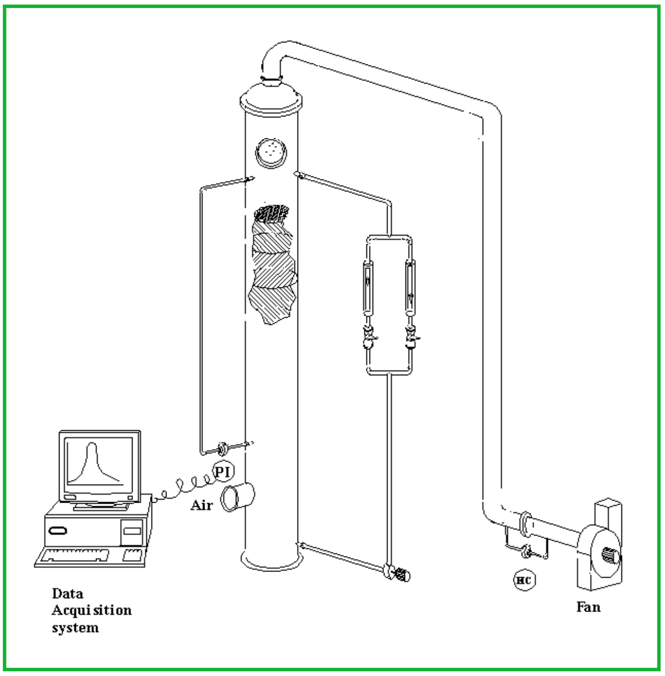

Figure 2 - Schematic drawing of the experimental apparatus

on the HelieR have only been reported by Launaro and Paglianti [2] in open literature and have been obtained on a very small laboratory apparatus.
The aim of the present work is to quantify the reduction in operating costs and compare the total cost when an absorption column is equipped with structured packings instead of traditional random packings.
The present work is composed of an experimental section followed by a theoretical analysis. The experimental part was carried out on a semi-industrial scale test column. The objective of this part was to make additional information available on the HelierR packing performances in terms of mass transfer efficiency and pressure drop thus allowing results to be compared with the performances of other packings. The experimental part is then followed by a theoretical analysis, aimed at comparing operating and total cost of columns packed with either random or structured packings.

Experimental Section

The properties required of a packing are great separation efficiency and high throughput with the minimum possible pressure drop in the gas stream. The better these requirements are met, the smaller is the volume of the equipment required for the given absorption task.
A criterion that is frequently adopted for evaluating packing performances is the pressure drop per theoretical stage (Billet [3]). Packings with low pressure drop per theoretical stage are essential for the realisation of optimum energy consumption which also entails a reduction in capital investments costs. To evaluate this parameter, mass transfer data as well as pressure drop measurements are required.
For the reasons described before, mass transfer efficiencies and pressure drops of the HelieR packing were investigated experimentally with the objectives of providing additional experimental data and comparing its performance to that of the other packings.

Experimental apparatus

Figure 2 shows a schematic drawing of the test-column designed and built for the experimental characterisation of packing performance in an absorption process. A picture of the experimental apparatus, located in the Department of Chemical Engineering, Industrial Chemistry and Materials Science of the University of Pisa (Italy), is shown in Figure 3.
The column is 6,700 mm height and has an inner diameter of 400 mm. It is equipped with 1.5" HelieR elements made from polypropylene, arranged to give a packing with an overall height of 2,000 mm. Because of the semi-industrial dimensions of the present column, scaling-up of experimental data can be done with a good degree of confidence.
In the present work, experimental tests were carried out on the absorption of sulphur dioxide in air into a sodium hydroxide solution. Due to the occurrence of an instantaneous irreversible reaction at the gas-liquid interface, the mass transfer is controlled almost entirely by the gas-phase resistance, therefore the mass transfer resistance in the liquid phase can be neglected. The overall gas phase mass transfer coefficient can therefore be easily evaluated by measuring inlet and outlet sulphur dioxide concentrations.
The set-up permits air rates in the range 80-200 m^3/hr and SO_2 rates in the range 40-100 Nl/h. Before entering the column, sulphur dioxide and air are fully-mixed by means of a static mixer element installed on line. The absorbent solution, containing 4 g/l of sodium hydroxide, is pumped from the storage tank to the top of the column with a continuous recycle. The concentration of NaOH in the washing solution is monitored by pH measurements.
The column can operate both by recycling washing solution and by using fresh absorption liquid.
Experimental tests were carried out at atmospheric pressure and room temperature. The absorption efficiency was measured by analysing the SO_2 content in the gas phase.
Samples of the inlet and outlet gas were taken using appropriate sample points and analysed using titration procedures. The pressure drop across the packing was measured by a Differential Pressure Transmitter and by a U-tube type manometer. In the upper section of the column, sign-glasses are present to permit monitoring for the occurrence of liquid entrainment.

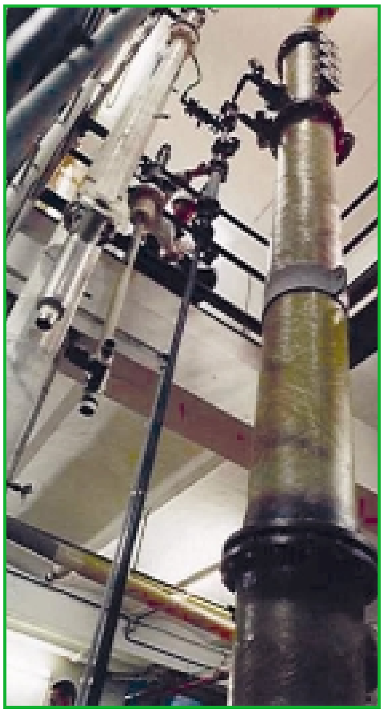

Figure 3 - Picture of the pilot column

Results and discussions

Figure 4 shows the specific pressure drop per theoretical stage as a function of the gas F-factor (F_v) for a commonly used specific liquid load of 21 $m^3/m^2/h$.
The diagram compares

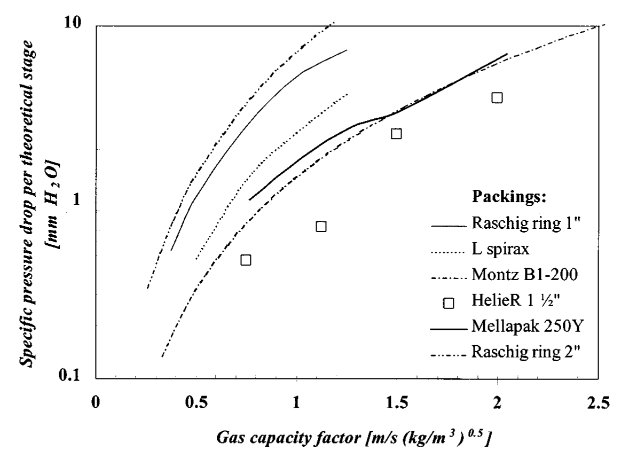

Figure 4 - Specific pressure drop per theoretical stage: comparison between HelieR $1^{1/2}$", Raschig 1" and Raschig 2" (Brunazzi et al. [4], Billet [3]), L-Spirax (Shimoi [5]), Montz B1-200 (Billet [6]); Mellapak 250Y (Launaro [6], Brunazzi and Paglianti [7]); liquid load 21 m³/m²/h

conventional random packings (Brunazzi *et al.* [4]), new type random packings (Shimoi [5]) and structured packings (Billet [3], Launaro [6], Brunazzi and Paglianti [7]).

Table 1 - Geometric characteristics of the analysed packings. Specific surface (a_e) and void fraction (*e*)

Packing type	*a_e (m²/m³)*	*e (-)*
HelieR $1^{1/2}$"	210	0.936
Mellapak 250Y	250	0.90-0.975
Montz B1-200	200	0.94-0.98
L - Spirax	94	0.90
Raschig 2"	100	0.90-0.92
Raschig 1"	200	0.90-0.92

Specific surface area and void fraction of the analysed packings are listed in Table 1. Figure 4 evidences that structured packings (Mellapak 250Y, Montz B1-200 and HelieR $1^{1/2}$") offer lower values of specific pressure drops per theoretical stage, that clearly entails a significant reduction in operating costs, compared to random packings (both the conventional and the new types). This behaviour is confirmed in Figure 5, which shows the annual operating cost of a theoretical stage per square meter of column section. For this analysis the operating energy associated with the movement of the gas stream, i.e. the energy consumed by the fan, has simply been considered. The operating cost has been computed assuming the energy cost equal to 0.1136 Euro/kWh and a fan efficiency of 65%. The figure shows that structured packings allow a 40-fold reduction in the operating costs with respect to random Raschig rings.
Figure 4 shows the specific pressure drops and it is interesting to highlight that these are comparable for all the structured packings analysed. The operating costs are shown in Figure 5 and are accordingly of the same magnitude for all the structured packings analysed.

Design Examples

The specific pressure drop per theoretical stage of a packing crucially governs the economics of absorption equipment. In this section, some simulations will be done to evaluate the effect of the choice of the packing on the operating and investment costs. All the simulations will refer to the absorption of NH_3 in air into a dilute HCl solution. The mass transfer resistance for this system is mainly in the gas phase (Meier *et al.* [8], Billet and Schultes [9]). A common specific liquid load of 21 m³/m²/h has been assumed for all the cases studied. This liquid load assures a good wetting rate for random packings, even if lower liquid loads could be used in columns equipped with structured packings.
The first simulation refers to a gas flowrate of 10,000 m³/h with a 300-fold reduction of NH_3 in gas concentration from 6 to 0.02 percent. To achieve these performances, about 6 transfer units are necessary.
Figure 6 shows the annual operating costs. These have been evaluated, as for Figure 5, considering the operating energy associated only with the movement of the gas phase and assuming an energy cost of 0.1136 euro/kWh. The figure shows that if a working F-factor of 1 is assumed, the operating costs of a column equipped with 2" Raschig rings are about 1,600 euro/year, whereas if a new type of random packing is used, e.g. L-Spirax, the costs decrease to about 500 euro/year, finally if a structured packing is used, e.g. Montz B1-200, Mellapak 250 Y or HelieR $1^{1/2}$", the operating costs are reduced to about 350 euro/year. This analysis suggests that, for this case, structured packings allow a reduction of about four-five times the operating costs compared with common random packings. But it is necessary to point out that the economic evaluation of a column packing also requires consideration as to the cost of the packing used.
The economic analysis on packed columns given in the following will take into account both the operating and the capital costs. For the reasons described above, the analysis will be limited to two widely used types of packing, the Raschig 2" ring and the Montz B1-200. These are respectively considered as representative of a common random and structured packing, the same approach can easily be extended to all other packings available on the market.

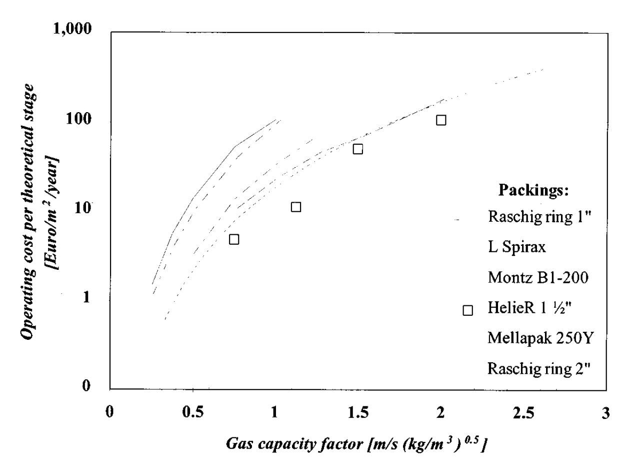

Figure 5 - Annual operating cost of a theoretical stage per square meter of column section; liquid load 21 m³/m²/h

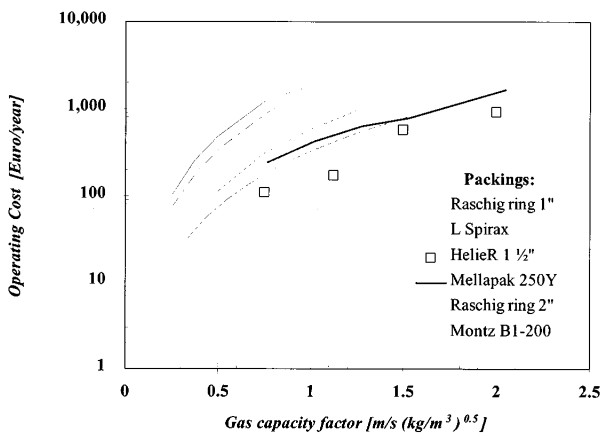

Figure 6 - Annual operating costs: comparison between common random, new type random and structured packings

In the following analysis the evaluation of the *operating costs* has been limited to the following items:
- power necessary to pump the liquid phase, the head has been assumed equal to the height of the packing;
- power necessary to move the gas phase, the head has been assumed equal to the pressure drop in the packing.

An energy cost of 0.1136 euro/kWh and an efficiency of 0.65 have been assumed. Operating costs have been updated using the following equation:

$$C_{op,\,actual} = C_{operating} \cdot \frac{1-(1+i)^{-n}}{i} \qquad (1)$$

where $C_{operating}$ is the cost per year, i is the rate of interest and n is the time duration of the investment.

The *capital costs* have been computed by taking into account the following items:
- the cost of the column. This item has been computed using the following empirical equation:

$$Cost_{column} = 583.6 \cdot D^{0.675} \cdot H \cdot F_{material} \cdot \left(\frac{P \cdot 14.5}{50}\right)^{0.44} \qquad (2)$$

where $Cost_{column}$ is given in Euro when D, the column diameter and H, the column height, are expressed in meters, and P, the working pressure, is given in kPa. The factor $F_{material}$ represents a correction to take into account for the cost of the material. Table 2 shows the values of $F_{material}$ used in present analysis.

Table 2 - Values of $F_{material}$ for some materials

Material	$F_{material}$
Carbon steel	1.0
Glass fiber	1.3
Stainless 304	1.7
Nickel 200	5.4

- The cost of the packing. This item has been evaluated multiplying the volume of the packing for the specific packing cost:

$$Cost_{packing} = \frac{\pi \cdot D^2}{4} \cdot H \cdot C \qquad (3)$$

where C is the specific cost of the packing. Table 3 shows the values of C used in present analysis.

Table 3 - Specific cost of packings

Packing type	*Packing material*	*C (euro/m³)*
Structured packing	Aisi 316	2,375.70
Structured packing	Polypropylene	3,356.97
Raschig ring 2"	Aisi 316	1,291.14
Raschig ring 2"	Polypropylene	206.58

Finally the total cost is given by

$$C_{tot}=(Cost_{column}+Cost_{packing})+C_{op,\,actual} \qquad (4)$$

Effect of column dimensions

In general the first problem to solve is to identify the column dimensions that allow the minimum total cost to be obtained once the time duration of the investment, n, is defined. Therefore the designer has to identify a range of column dimensions (i.e. diameter and height), that could be used from the fluid-dynamics point of view and from that range he has to choose the dimensions that result in the lowest total cost. Figures 7a and 7b show the investment, operating and total costs as a function of the F-factor for columns equipped with random (Raschig ring 2") and structured (Montz B1-200) packings respectively.

The material of the column is stainless steel Aisi 304, the packings are made from stainless steel Aisi 316. The present simulation refers to the absorption of NH_3 in dilute HCl with a 300-fold reduction in gas concentration from 6 to 0.02 percent, the gas flowrate is 10,000 m³/h. The time duration of investment is 5 years.

The analysis of the figures clearly shows that the capital cost for columns equipped with structured packings is higher than the cost for columns equipped with random packings whereas the operating costs are higher for columns equipped with random packings. This result is rather obvious, nevertheless an accurate analysis of the figures shows that the optimum F-factor for columns equipped with structured packings is higher than the F-factor related to columns equipped with random packings, therefore, if structured packings are used, it is possible to use smaller column diameters. It can also be seen that, in this case, the minimum total cost for columns equipped with structured packings is lower than the minimum total cost obtained with columns equipped with random packings. This result is not obvious; in fact, because of their high cost per cubic meter, designers only usually tend to use structured packings when low pressure drops are necessary, e.g. equipment working under vacuum conditions. From the analysis of the Figures 7a and 7b it emerges that this approach could be wrong and

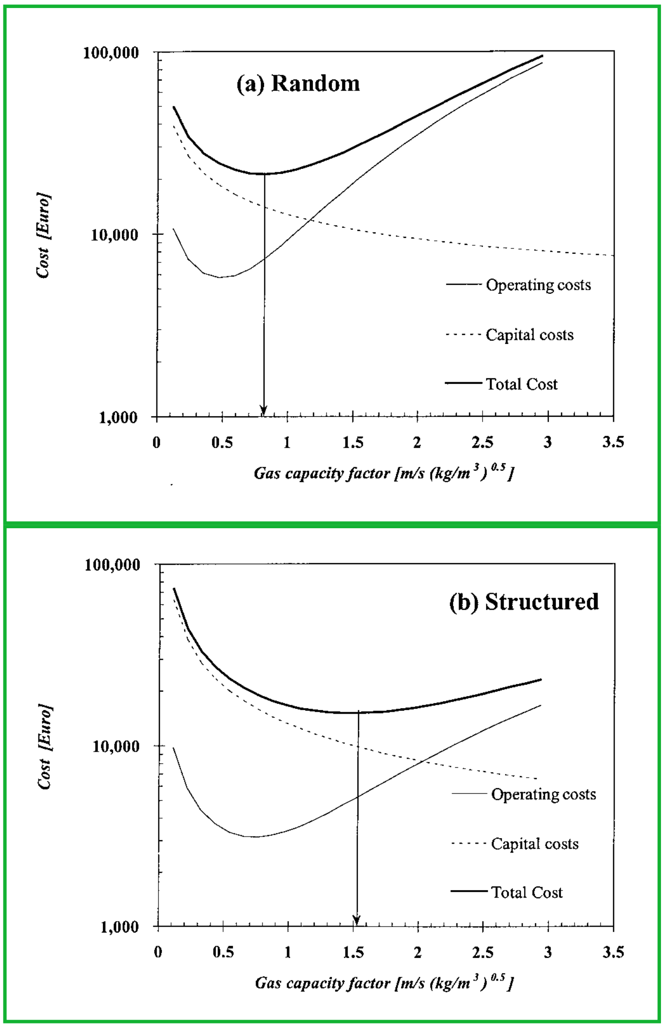

Figure 7 - Capital, operating and total costs as a function of F-factor for column equipped with (a) Raschig ring 2" (packing in Aisi 316 material and column vessel in Aisi 304 material)
(b) Montz B1-200 (packing in Aisi 316 material and column vessel in Aisi 304 material)

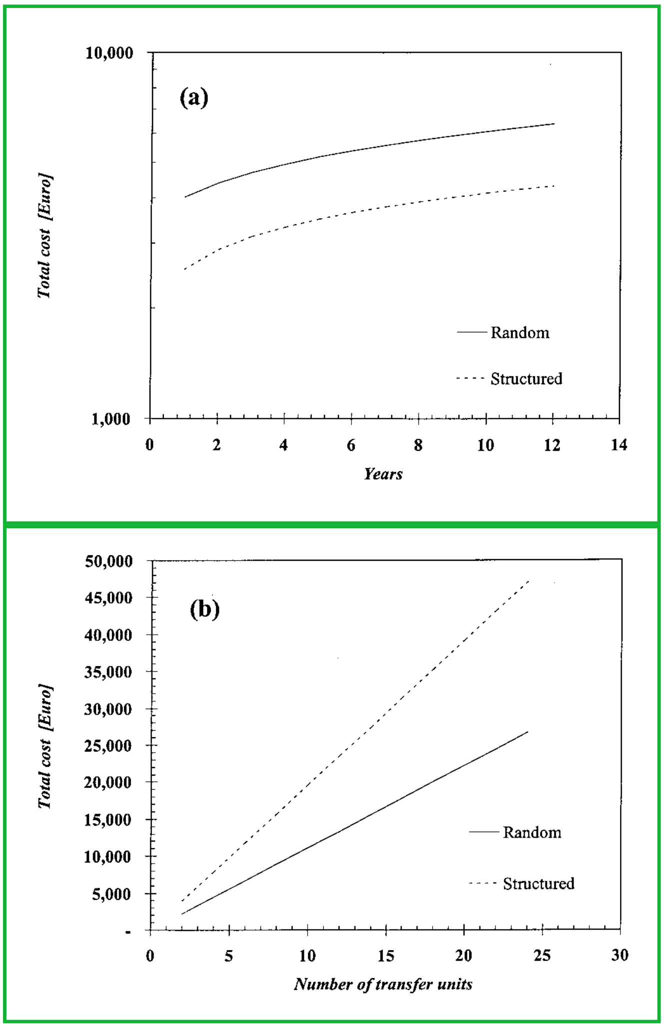

Figure 8 - Miminum total costs: comparison between structured and random packings. (a) The influence of the time duration of investment (column vessel in Aisi 304 and packings in Aisi 316); (b) The influence of the number of transfer units (column vessel in glass fiber and packings in polypropylene)

that the use of structured packings, despite their higher cost per cubic meter, would allow the total cost of the process to be reduced.

Effect of the time duration of investment and of the number of transfer units

The following section will analyse the influence of the time duration of investment and of the number of transfer units.

Figure 8a shows the minimum total costs as a function of the time duration of investment. The material of the column is stainless steel Aisi 304, the packings are made from stainless steel Aisi 316. The present simulation refers to the absorption of NH_3 in dilute HCl with 10 transfer units, the gas flowrate is 1,000 m^3/h. The figure clearly shows that columns equipped with structured packing are cheaper than columns equipped with random packing in all the cases.

This result is quite surprising since if the time duration of investment is short, the operating costs have a negligible effect and the total cost is essentially due to the capital costs. Figure 8a shows that structured packings are more economical even if the time duration of investment is equal to 1 year. This means that, for the present case, capital costs of column equipped with structured and random packings are comparable. The capital costs are depend on both to the packings and to the absorption column vessel. In the present case, the vessel containing the random packing is much greater than the vessel containing the structured packing and therefore the capital costs are found to be comparable. In fact, if the case with 1 year as time duration of investment is analyzed, the column containing structured packing has a diameter of 0.4 m and is 3.3 m high, whereas the column containing random packing has a diameter of 0.6 m and is 4.6 m high. Therefore the material cost of the vessel and of the packing is extremely important in the economic analysis.

Figure 8b shows the economic simulations for the absorption of NH_3 in air into a dilute HCl solution with a gas flowrate of 6,000 m^3/h. The required number of transfer units are varied by imposing different reductions of NH_3 concentration in the gas stream. A glassfiber column is considered and the packings are made from polypropylene. The time duration of the investment is 5 years. The figure clearly shows that, as opposed to the previous example, columns equipped with random

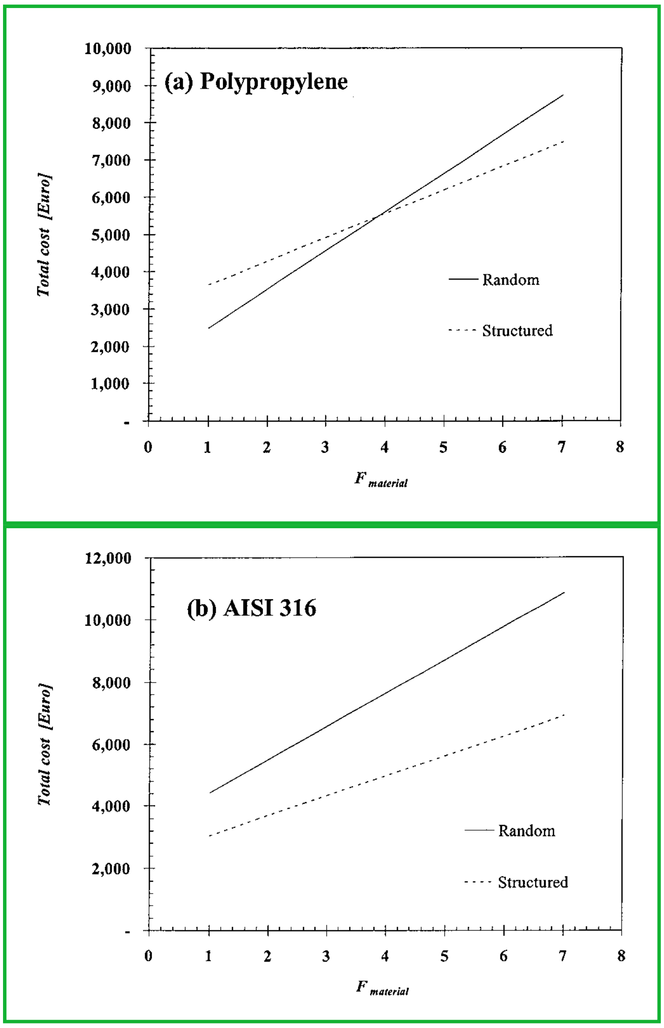

Figure 9 - Minimum total cost as a function of vessel material, comparison between structured and random packings.
(a) packings made from polypropylene (b) packings made from Aisi 316

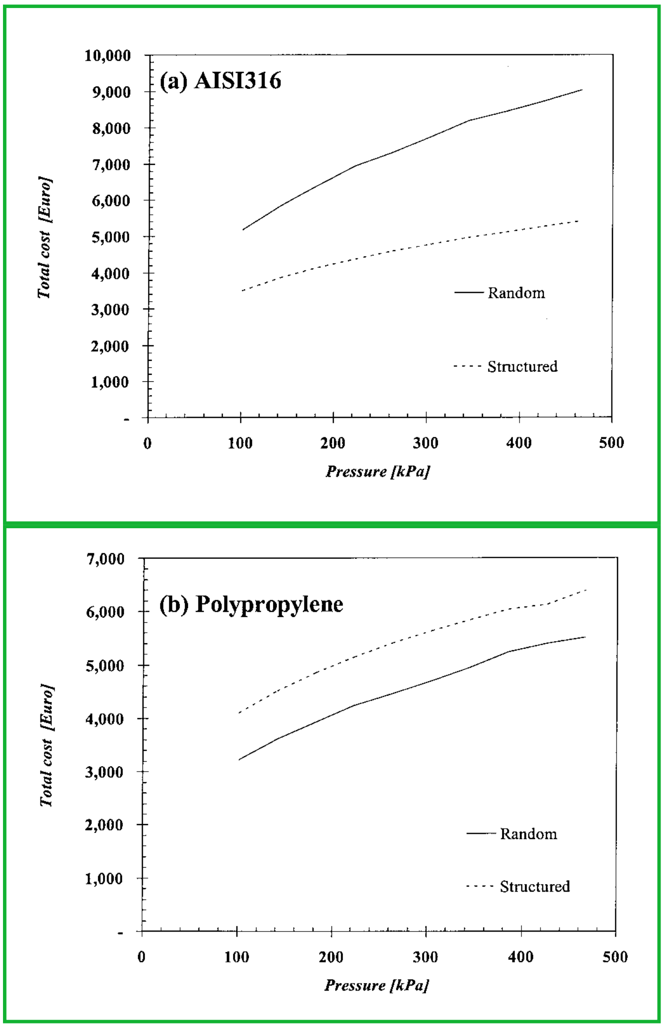

Figure 10 - Minimum total cost as a function of operating pressure, comparison between structured and random packings (column vessel in Aisi 304, 10 transfer units, gas flowrate 1,000 m^3/h, time duration of investment 5 years) (a) packings made from Aisi 316 (b) packings made from polypropylene

packing are cheaper than columns equipped with structured packings in all cases.
This result is due to two reasons, firstly the lower cost of random packing made from polypropylene compared to the cost of structured packing in polypropylene and secondly, the lower cost of the vessel compared to the vessel made from Aisi 304.

Packing and vessel materials, working pressure and gas flow rate

In order to perform a correct economic design of an absorption column it is necessary to look at the influence of both the packing and the vessel materials.
Figure 9a shows the economic simulations as a function of the cost of the vessel material for the case of absorption of NH_3 in dilute HCl with a gas flowrate of 1,000 m^3/h and 10 transfer units. The packing material is polypropylene and a 5 year investment time duration is considered. This simple analysis suggests a general rule: work with polypropylene packings if the vessel is made of a cheap material, such as Carbon steel $F_{material}$=1; in this case it is more economical to use random packings, whereas if the vessel is made from expensive material, such as Nickel 200 $F_{material}$=5.4, it is more convenient to reduce the vessel dimensions and to to use structured packings, as shown in Figure 9a. If, however, the same absorption process is performed using packing made from Aisi 316, the best economic performances are obtained if structured packings are used, indipendently of the material used for the vessel, as shown in Figure 9b. The same behaviour is also be noticed when the column operating pressure (Figures 10a-10b) or the gas flowrate (Figures 11a-11b) is varied. If stainless steel Aisi 316 is used as the packing material, the best economic performances can be obtained using structured packings, whereas if the packings are made from Polypropilene, it is cheaper to use random packings.

Conclusions

Experimental results performed under industrial operating conditions and theoretical computations made using relations available in open literature have shown that structured packings, e.g. HelieR, Mellapak 250Y or Montz B1-200, can offer very low pressure drops per theoretical stage. The good performance of these packings allow the operating costs of a col-

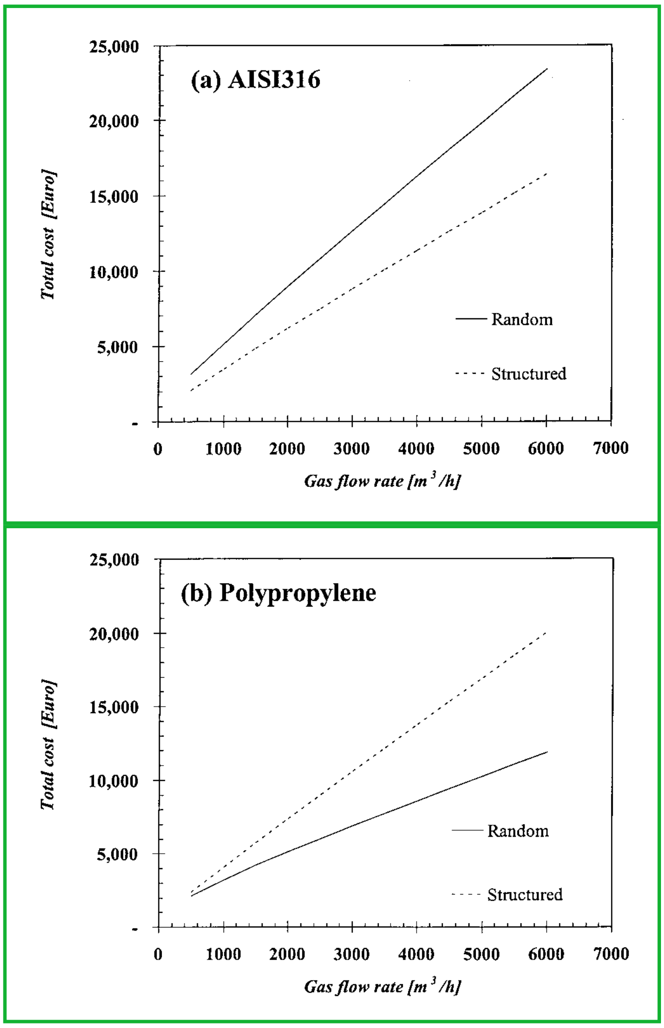

Figure 11 - Minimum total cost as a function of gas flowrate; comparison between structured and random packings (column vessel in Aisi 304, operating pressure 101.3 kPa, 10 transfer units, 5 year time duration of investment) (a) packings made from Aisi 316 (b) packings made from polypropylene

umn to be reduced drastically and they result in a reduction of the investment costs as well.

The correct design of an absorption column has not just to take into account the cost per cubic meter of the packing, but also the operating and capital costs of the column. The results obtained in the present work show that an economical analysis of the columns allows large savings of money to be made.

The economical analysis has taken into account the cost of the packings together with the cost of the column and the operating costs.

Nomenclature

a_e	= packing specific area, [m^2/m^3]
C	= specific packing cost, [euro/m^3]
$Cost_{column}$	= column vessel cost, [euro]
$Cost_{packing}$	= packing cost, [euro]
$C_{op,actual}$	= updated operating cost, [euro]
$C_{operating}$	= annual operating cost, [euro/year]
C_{tot}	= total updated cost, [euro]
D	= column diameter, [m]
e	= packing void fraction, [-]
$F_{material}$	= vessel material factor, [-]
Fv	= $U_{sg}(\rho_g)^{0.5}$, gas capacity factor, [m/s(kg/m^3)$^{0.5}$]
i	= rate of interest, [-]
H	= packing height, [m]
n	= time duration of investment, [year]
NUT	= number of transfer units
P	= operating pressure, [kPa]
U_{sg}	= superficial gas velocity, [m/s]
π	= 3.14159…
ρ_g	= gas density, [kg/m^3]

References

[1] G. Parkinson, G. Ondrey, *Chem. Eng.,* 1999, **106** (13), 39.

[2] P.Launaro, A. Paglianti, *Ind. Eng. Chem. Res.,* 1999, **38,** 3481.

[3] R. Billet, Packed Column Analysis and Design, Ruhr-Universität Bochum, Dept. of Thermal Separation Processes, Germany 1989.

[4] E. Brunazzi, A. Paglianti, L. Petarca, *Chim. Ind.,* 1996, **78**, 459.

[5] Y. Shimoi, Gas Absorption Manual, Nittetu Chemical Engineering Ltd., Kumekawa Printing Co. Ltd, (Tokyo, Japan) 1991.

[6] P. Launaro, *M.Sc. Thesis,* (The University of Pisa, Italy) 1997.

[7] E. Brunazzi, A. Paglianti, *AIChE J.,* 1997, **43,** 317.

[8] W. Meier, W.D. Stoecker, B. Weinstein, *C.E.P.,* 1977, 71.

[9] R. Billet, M. Schultes, *Chem. Eng. Technol.*, 1993, **16,** 1.