An Economical Criterion for Packed Absorption Column Design

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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.

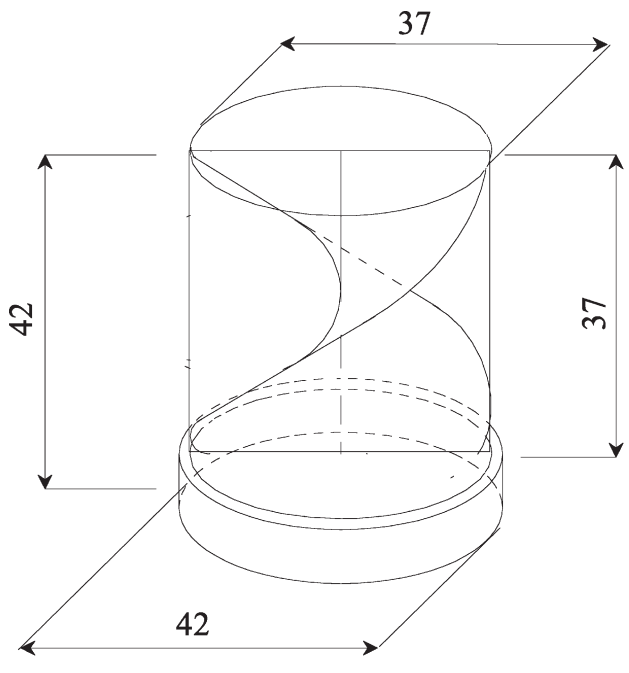
In the present work, besides some new experimental data on pressure drop and mass transfer efficiency of a new structured packing, an economic analysis on column packings has been performed. The results show that, in some cases, structured packings can save energy and significantly reduce the operating and investment costs by offering reduced values of pressure drops per transfer unit in comparison to conventional dumped packing. In some other cases columns equipped with random packings give better economical performances than columns equipped with structured packings. The economical analysis has been performed analysing the effects of a number of variables (e.g. column dimensions, working pressure, gas flow-rate, packing or vessel material, absorption efficiency and depreciation period).

Key words:
Absorption, structured packings, operating cost, economic analysis, packed columns

Introduction

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 reducing 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 S.r.l., made of 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 volumic cost of structured type packings is higher than the cost for common random packings. However, it is well known that structured packings offer lower pressure drops per transfer unit, thus reducing energy consumption and hence operating costs. In addition, *Parkinson* and *Ondrey*[1] also explain that structured packings are favoured over less-expensive random packings because they allow a more predictable scale-up of a column.



F i g . 1 – *Schematic drawing of the HelieR element (dimension in millimetres)*

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 litera-

*To whom correspondence should be addressed ture. 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 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 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 HelieR packing performances in terms of mass transfer efficiency and pressure drop, thus allowing results to be compared with the performances of other packings. The properties required to 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 needed for the given absorption task. A criterion that is frequently adopted for evaluating packing performances is the pressure drop per transfer unit (*Billet*[3]). Packings with low pressure drop per transfer unit are essential for the realisation of optimum energy consumption which also entails a reduction in purchasing costs. To evaluate this parameter, mass transfer data as well as pressure drop measurements, are required.

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. The objective of the present work is to suggest a procedure for optimising the absorption column design. In other words it will be shown that, according to the working conditions, it is possible to identify when structured packings allow reducing the sum of purchasing and operating costs and whereas, when it is cheaper using common random packings. It is important to underscore that the following procedure can be used also with different packings (e.g. the new generation of random packings) if volumic costs, pressure drop and number of transfer units per meter, are known.

Experimental section

Because of the reasons described in the Introduction, 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.

Figure 2 shows a schematic drawing of the test-column designed and built for the experimental characterisation of packing performance in an absorption process, located in the Department of Chemical Engineering, Industrial Chemistry and Materials Science of the University of Pisa (Italy).

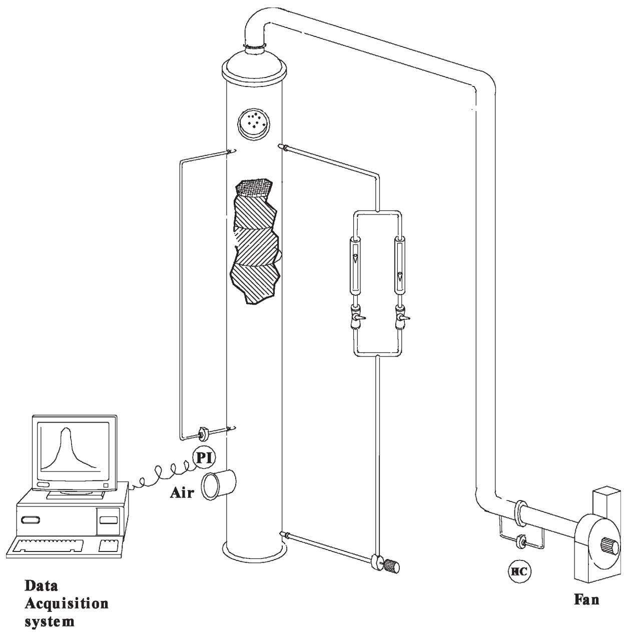


Fig. 2 – *Schematic drawing of the experimental apparatus*

The column is 6700 mm heigh and has an inner diameter of 400 mm. It is equipped with $1\frac{1}{2}$" HelieR elements made from polypropylene, arranged to give a packing with an overall height of 2000 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.

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 flow rates in the range 80 to 200 $m^3\ h^{-1}$ and SO_2 rates in the range 40 to 100 $l\ h^{-1}$, at normal conditions. 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^{-1} of sodium hydroxide, is pumped from the storage tank to the top of the column with a continuous recycle. The mass 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 (*Launaro*[4]). 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.

Results and discussions

Figure 3 shows the pressure drop per transfer unit as a function of the gas *F-factor* (F_v) for a commonly used liquid load of 21 m^3 m^{-2} h^{-1}. Figure shows some experimental trends available in the literature (e.g. Raschig ring 1″ and Raschig ring 2″ (*Billet*[3], *Brunazzi* et al.[5]), L Spirax (*Shimoi*[6]), Montz B1–200 (*Billet*[3]), Mellapak 250Y (*Brunazzi* and *Paglianti*[7])), and some new experimental data obtained in present work (HelieR 1 ½").

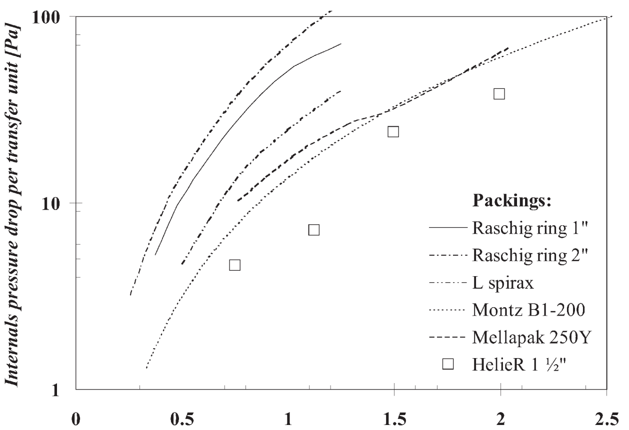


Fig. 3 – *Pressure drop per transfer unit: comparison between HelieR 1½", Raschig 1" and Raschig 2" (Brunazzi et. al*[5]*, Billet*[3]*), L-Spirax (Shimoi*[6]*), Montz B1–200 (Billet*[3]*); Mellapak 250Y (Brunazzi and Paglianti*[7]*); liquid load 21* m^3 m^{-2} h^{-1}

Volumic area and void fraction of the analysed packings are listed in Table 1. Figure 3 shows that structured packings (Mellapak 250Y, Montz B1–200 and HelieR 1½") offer lower values of pressure drops per transfer unit, what 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 4, which shows the annual operating cost of a transfer unit per unit cross 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 EUR kWh^{-1} and a fan efficiency of 65 %. The figure shows that structured packings allow reducing the operating costs to 1/40 with respect to random Raschig rings.

Table 1 – *Geometric characteristics of the analysed packings. Volumic area* (a_e) *and void fraction* (e)

Packing type	$\frac{a_e}{m^2\ m^{-3}}$	$\frac{e}{-}$
HelieR 1½"	210	0.936
Mellapak 250Y	212–250	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

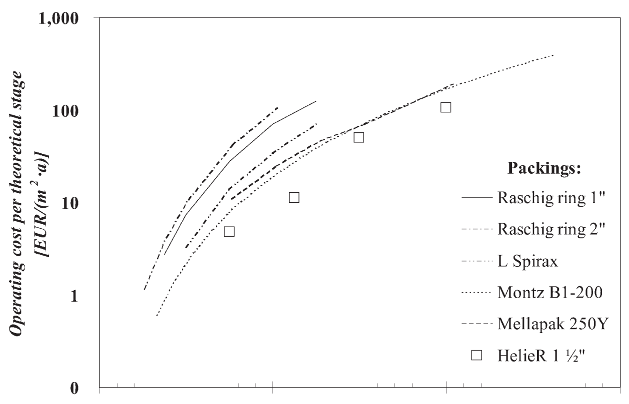


Fig. 4 – *Annual operating cost of a transfer unit per unit column cross-section; liquid load 21* m^3 m^{-2} h^{-1}

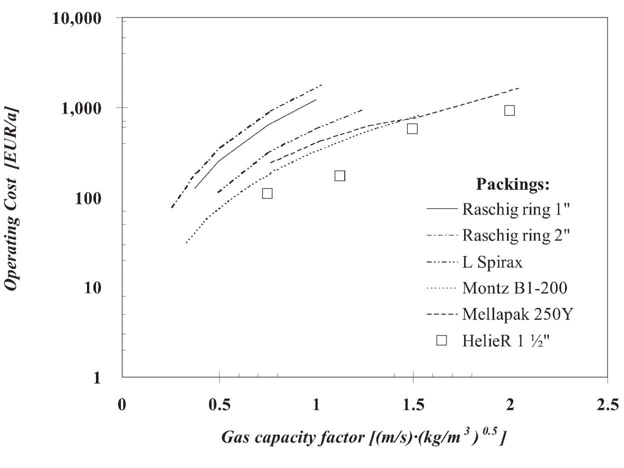
Figure 3 shows the column internals pressure drops and it is interesting to highlight that those are comparable for all the structured packings analysed. The operating costs are shown in Figure 4 and are accordingly of the same magnitude for all the structured packings analysed.

Design examples

The pressure drop per transfer unit 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 purchasing 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 liquid load of 21 $m^3\ m^{-2}\ h^{-1}$ 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 flow rate of 10.000 $m^3\ h^{-1}$ with a reduction in the NH_3 gas volume fraction from 6 % to 0.02 %. To achieve these performances, about 6 transfer units are necessary.

Figure 5 shows the annual operating costs. These have been evaluated, as for Figure 4, considering the operating energy associated only with the movement of the gas phase, and assuming an energy cost of 0.1136 EUR kWh^{-1}. 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 1600 EUR a^{-1}, whereas, if a new type of random packing is used, e.g. L-Spirax, the costs decrease to about 500 EUR a^{-1}, 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 EUR a^{-1}. This analysis suggests that, for this case, structured packings allow reducing the operating costs of about 1/4 to 1/5 compared with common random packings. But it is necessary to point out that the economic evaluation of a column packing also requires consideration to the cost of the packing used.



F i g . 5 – *Annual operating costs: comparison between common random, new type random and structured packings. (Absorption system:* NH_3 *in air into a diluite HCl solution)*

The economic analysis of packed columns given in the following will take into account both the operating and the purchasing 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 considered as representative of a common random and structured packing respectively, the same approach can easily be extended to all other packings available on the market.

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 being assumed equal to the height of the packing

– power necessary to move the gas phase, it has been computed using the pressure drop in the packing.

An energy cost of 0.1136 EUR kWh^{-1} and an efficiency of 0.65 have been assumed. Total operating costs, spent during the t years, have been updated using the following equation:

$$C_{\mathrm{op,act}} = C_{\mathrm{op}} \cdot \left[\frac{1-(1+i)^{-t}}{i} \right], \qquad (1)$$

where C_{op} is the cost per year, i is the rate of interest and t is the depreciation period.

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:

$$C_{\mathrm{col}} = 583.6 \cdot d^{0.675} \cdot h \cdot F_{\mathrm{mat}} \cdot \left(\frac{p \cdot 14.5}{50} \right)^{0.44}, \qquad (2)$$

where C_{col} is given in EUR 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_{mat} represents a correction to take into account for the cost of the material. Table 2 shows the values of F_{mat} used in present analysis.

T a b l e 2 – *Values of* F_{mat} *for some materials*

Material	F_{mat}
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 volumic packing cost:

$$C_{\text{pac}} = \frac{\pi \cdot d^2}{4} \cdot h \cdot C, \tag{3}$$

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

Table 3 – *Volumic cost of packings*

Packing type	Packing material	C / EUR m^{-3}
Structured packing	AISI 316	2375.70
Structured packing	Polypropylene	3356.97
Raschig ring 2"	AISI 316	1291.14
Raschig ring 2"	Polypropylene	206.58

Finally the total cost is given by

$$C_{\text{tot}} = (C_{\text{col}} + C_{\text{pac}}) + C_{\text{op, act}} \tag{4}$$

It is necessary to point out that in the present analysis the cost to install the equipment has not been taken into account, being strictly the function of the country where plant is built. This is a great simplification but, it is necessary to underscore, that the main objective of present work is to show that the correct design of an absorption column cannot be done, taking into account only technical details (e.g. capacity, loading point or flooding point), but it is necessary to take into account also the economical point of view. Therefore if some details are available on the cost necessary to install the equipment, it is sufficient to introduce another term on the right side of the Eq. 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 depreciation period, t, is defined. Therefore, the designer has to identify a range of column dimensions (i.e. diameter and height), that could be used from the fluidodynamics point of view, and from that range he has to choose the dimensions that result in the lowest total cost. Figures 6a and 6b 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 reduction in the NH_3 gas volume fraction from 6 % to 0.02 %, the gas flow rate is 10.000 m^3 h^{-1}. The depreciation period is 5 years.

The analysis of the figures clearly shows that the total purchasing cost for columns equipped with structured packings are 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 volumic cost, designers usually tend to use structured packings only when low pressure drops are necessary, e.g. equipment working under vacuum conditions. From the analysis of the Figures 6a and 6b it emerges that this approach could be wrong and that the use of structured packings, despite their higher volumic cost, would allow the total cost of the process to be reduced.

Figures 6a and 6b advice another important design consideration. Usually designers choose the gas velocity in the column as the gas velocity at the loading point, and thereafter compute the column diameter. Figures 6a and 6b show that this rule of thumb might be inadequate, in fact, in the present case study, the value of the gas capacity factor allowing a reduction of the total costs, C_{tot}, is absolutely lower than the capacity factor at the loading point.

Effect of the depreciation period and of the number of transfer units

The following section will analyse the influence of the depreciation period and of the number of transfer units.

Figure 7a shows the minimum total costs, obtained as described above (see e.g. Figures 6a and 6b), as a function of the depreciation period. 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 of 1.000 m^3 h^{-1}. The figure clearly shows that columns equipped with structured packing are cheaper than columns equipped with random packing in all the cases.

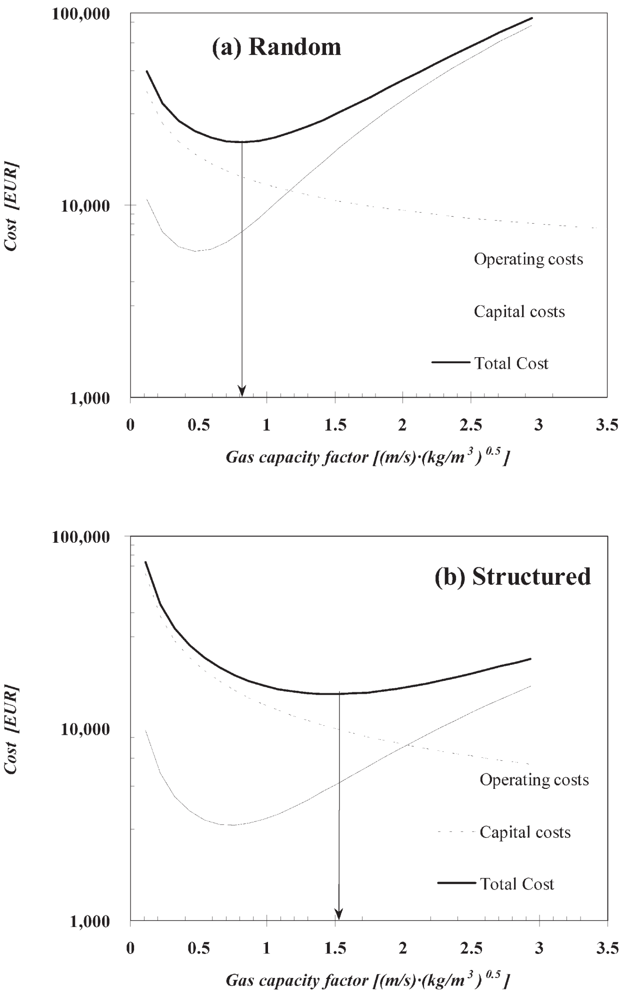


Fig. 6 – *Capital, operating and total costs as a function of F-factor for column equipped with (a) Raschig ring 2" (packing in AISI 316 material and column vessel in AISI 304 material); (b) Montz B1–200 (packing in AISI 316 material and column vessel in AISI 304 material). (Absorption system: NH_3 in air into a dilute HCl solution).*

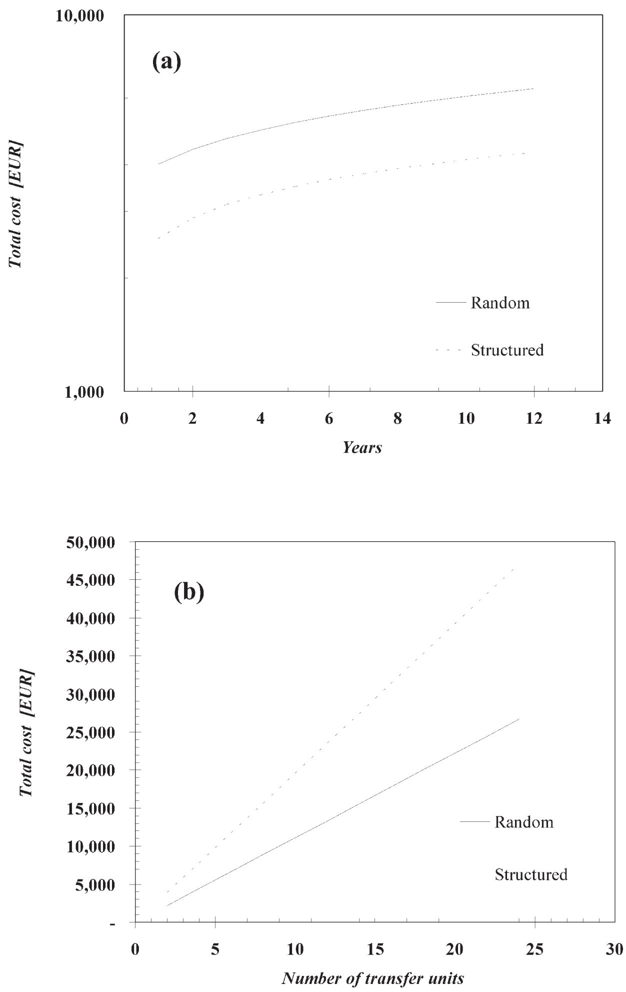


Fig. 7 – *Minimum total costs: comparison between structured and random packings. (a) The influence of the depreciation period (column vessel in AISI 304 and packings in AISI 316); (b) The influence of the number of transfer units (column vessel in glass fiber and packings in polypropylene). (Absorption system: NH_3 in air into a dilute HCl solution).*

This result is quite surprising since if the depreciation period is short, the operating costs have a negligible effect and the total cost is essentially due to the capital costs. Figure 7a shows that structured packings are more economical even if the depreciation period is equal to 1 year. This means that, for the present case, the capital costs of columns equipped with structured and random packings, are comparable. The purchasing costs depend on both the packing and 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 purchasing costs are found to be comparable. In fact, if the case with 1 year as depreciation period is analysed, 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 7b shows the economic simulations for the absorption of NH_3 in air into a dilute HCl solution with a gas flow rate at 6.000 $m^3\ h^{-1}$. 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 depreciation period is 5 years. The figure clearly shows that, as compared with the previous example, columns equipped with random packings 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.

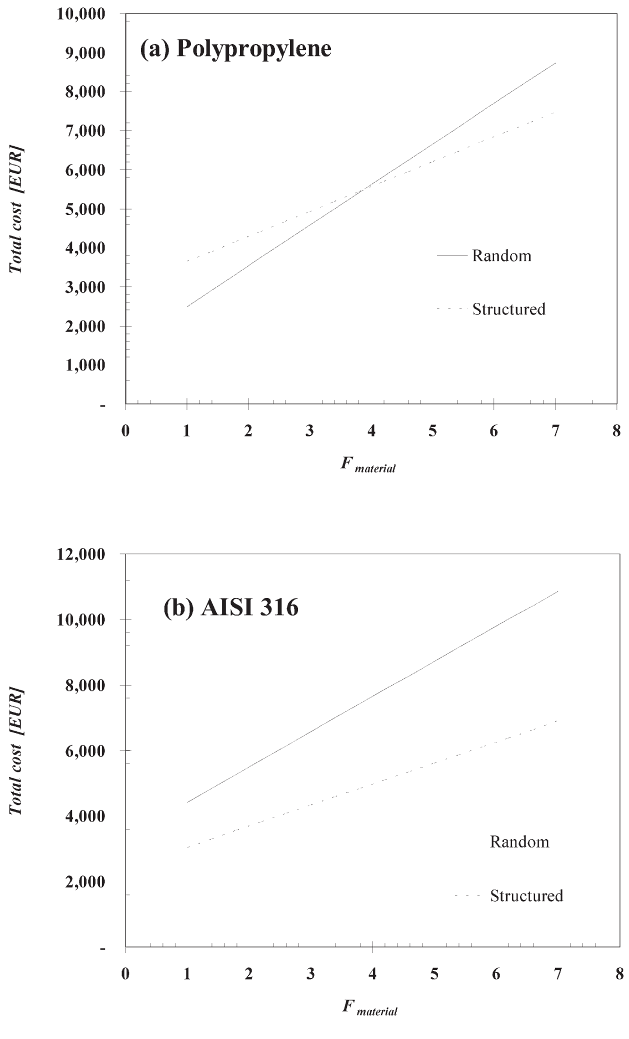
Packing and vessel materials, working pressure and gas flow rate

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 8a 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 flow rate of 1.000 m^3 h^{-1} and 10 transfer units. The packing material is polypropylene and a 5 year depreciation period is considered.

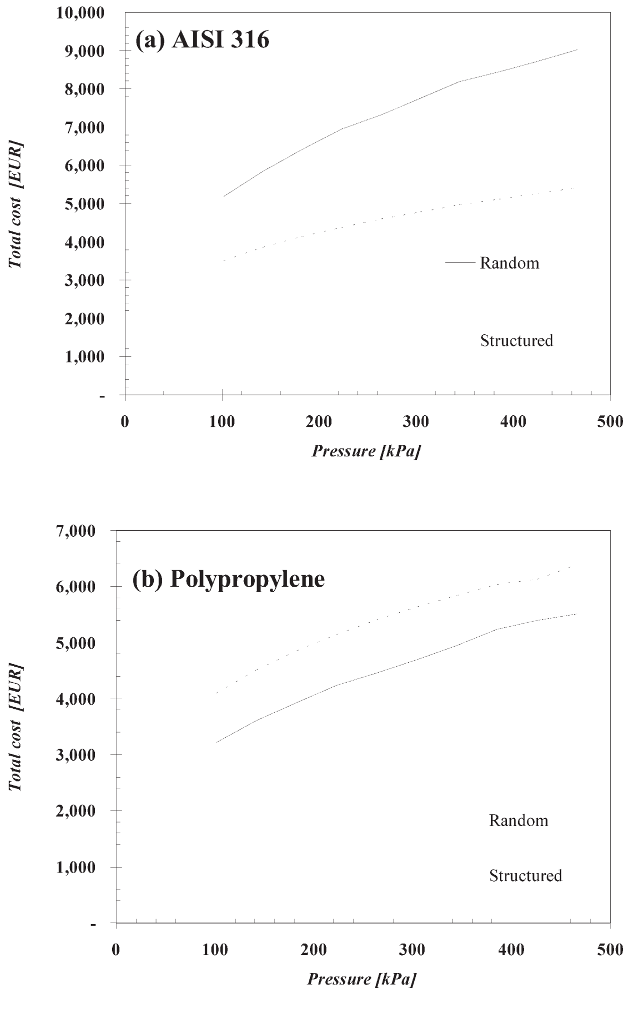
This simple analysis suggests a general rule: work with polypropylene packings if the vessel is made of a cheap material, such as Carbon steel, F_{mat} = 1; in this case it is more economical to use random packings, whereas if the vessel is made from expensive material, such as Nickel 200, F_{mat} = 5.4, it is more convenient to reduce the vessel dimensions and to use structured packings, as shown in Figure 8a.

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 8.b.

The same behaviour is also noticed when the column operating pressure (Figures 9a-9b) or the gas flow rate (Figures 10a-10b) 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 Polypropylene, it is cheaper to use random packings.



F i g . 8 – *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. (Absorption system: NH_3 in air into a dilute HCl solution).*



F i g . 9 – *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^{-1}, depreciation period 5 years), (a) packings made from AISI 316; (b) packings made from polypropylene. (Absorption system: NH_3 in air into a dilute HCl solution).*

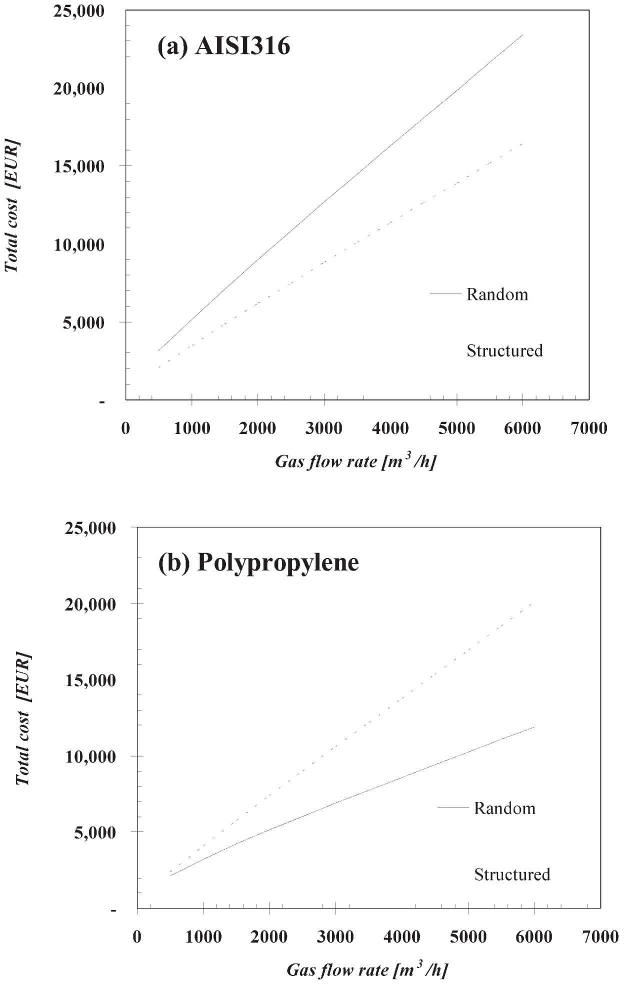


Fig. 10 – *Minimum total cost as a function of gas flow rate; comparison between structured and random packings (column vessel in AISI 304, operating pressure 101.3 kPa, 10 transfer units, 5 year depreciation period), (a) packings made from AISI 316; (b) packings made from polypropylene. (Absorption system: NH_3 in air into a dilute HCl solution).*

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 transfer unit. The good performance of these packings allow the operating costs of a column to be reduced drastically and they result in a reduction of the purchasing costs as well.

The correct design of an absorption column has not just to take into account the volumic cost of the packing, but also the operating and purchasing 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 only the cost of the packings together with the cost of the column and the operating costs, but it can be easily implemented also to take into account other costs (e.g. the cost necessary to install the equipment).

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Nomenclature

a_e – packing volumic area, m^2 m^{-3}
C – packing volumic cost, EUR m^{-3}
C_{col} – column vessel cost, EUR
C_{pac} – packing cost, EUR
$C_{op,act}$ – updated operating cost, EUR
C_{op} – annual operating cost, EUR a^{-1}
C_{tot} – total updated cost, EUR
d – column diameter, m
e – packing void fraction, –
F_{mat} – vessel material factor, –
Fv – u_{sg} $(\rho_g)^{0.5}$, gas capacity factor, (m s^{-1}) · (kg m^{-3})$^{0.5}$
i – rate of interest, –
h – packing height, m
t – depreciation period, year
p – operating pressure, kPa
u_{sg} – superficial gas velocity, m s^{-1}
π – 3.14159…
ρ_g – gas density, kg m^{-3}

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