Fluid Distribution in Packed Beds. Part 1. Literature and Technology Overview

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1. INTRODUCTION

The literature reports a lot of relations and experimental data sets to describe the efficiency and fluid-dynamic behavior of random and structured packings. They are aimed at the rigorous and reliable design of unit operations with packed beds.

Conversely, the study, design, and operation of fluid distributors and particularly their interactions with the beneath packed beds are still a relatively unexplored area. For instance, no design criteria are available, regarding the optimal distance between the distributor and packed bed.

Liquid distributors are complex and expensive elements of the distillation columns which are aimed to uniformly distribute the liquid over the packing. Their main parameters are the drip point density and their structure with regard to the underlying packing. The drip point can be arranged forming square, rectangular, or triangular pitches. Since the number of drip points cannot be infinite, a fraction of the first packing layer remains unwetted, giving place to a loss of separation efficiency.

Actually, the use of well-designed distributors, the knowledge and deep understanding of their behavior under conventional and nonconventional operating conditions, and finally their interactions with the packing are all key points to exploit at best the potentialities of the structured packing and, thus, of the whole unit operation.

To emphasize the technological interest in investigating the behavior of fluid distributors, it is enough to mention that the real performance of structured packing columns can be significantly lower than expected whenever the distributor is not designed accordingly. Lockett and Billingham[1] in their work show a quantitative effect of maldistribution that can multiply by 5 or more the effective number of theoretical stages. Albright[2] stated that the liquid flow tends to a natural distribution. If a distribution of liquid better than the natural distribution is performed by the distributor, the system quickly restores its natural distribution: in some cases, it is possible to observe a worsening distribution compared to the initial one. Conversely, after a poor initial liquid distribution, gradually the flow reaches its natural distribution. The time necessary to reach the natural distribution depends on the random structure of the packed beds, on the type and size of the packings, on the design of the liquid distributor, and on the gas and liquid flow rates.

Bonilla[3] devoted an extended paper to the description of problems related to liquid maldistribution in packed systems, pointing out the importance of a good liquid distribution particularly in the case of highly extended surface systems like structured packings. He described the distributor evaluation and design and the procedures for distributor testing.

Spekuljak and Monella[4] reported the problems of structured packing column malfunctions originated by the flow distribution. These troubles, usually, were more dramatic in revamped columns, where a significant increase in the column throughput or/and the product specification was expected. However, the result was a loss in the column efficiency.[4]

Despite their importance, the effects of gas and liquid maldistributions are often masked by over-dimensioned packed beds,[5,6] which only have the task of recovering in an expensive way what can be clearly often solved with a proper packed column design coupled with a good characterization and investigation of the behavior of fluid distributors. However, as stated by Bonilla, an increase of bed height does not work because the already formed gradients in the column cannot be compensated due to the rate of response of the system.

The study of liquid distribution is especially important if one looks at the increasing use of packed columns in distillation and absorption/stripping processes. A good understanding and

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prevision of the flow paths in the packing can produce the reduction of the column height and the consequent reduction of the investment and variable costs. It is worth remarking that these items of cost easily increase with the height equivalent theoretical plate (HETP),[5,6] rising with the maldistribution.

2. LIQUID MALDISTRIBUTION

Fluid distribution in packed columns is in general not uniform, especially in the liquid phase. Maldistribution of fluids is always responsible for a significant reduction in the transfer efficiency requiring additional HETP to match the packed column specifications. Liquid distribution depends on the distributors and on the packing that is adopted in the column. Liquid distributes along the packing in relation to the channeling and differences of permeability between the wall region and the bulk region. A macroanalysis of the problem can be made by separating into random and structured packing systems. Maldistribution can be caused by the distributor, by the geometrical characteristics of the packing, or by the interactions between the gas and liquid flows.

2.1. Random Packings. It is normally accepted that for this kind of packing the gas doesn't need additional distribution because the high pressure drop acts as a flow distributor. The major problem is then to adequately distribute the liquid inside the system even if the importance of the interaction with gas flow becomes more and more evident with the deepening of knowledge. The problem of liquid distribution became increasingly evident with the modification of dumped packing geometry aimed to improve the efficiency of the separation. A traditional method to analyze liquid maldistribution is based on the use of a specially designed collecting vessel, installed below the packing bed to collect liquid falling down. Other methods are tracing methods, conductance processes, and tomographic measurement techniques,[7] which however are very complicated systems, limiting their application. The quality of liquid distribution is frequently measured by adopting a maldistribution factor, Mf, defined starting from Hoek[8] and based on the use of a collecting vessel for measuring liquid distribution across the column section. The Mf is defined as follows:

$$\mathrm{Mf} = \frac{1}{n}\left[\sum_i \left(1 - \frac{Q_i}{Q_{\mathrm{av}}}\right)^2\right]^{0.5} \tag{1}$$

where n is the total number of collecting cells in the liquid collecting device, Q_i is the volumetric flow rate to the ith collecting cell, and Q_{av} is the mean value of the volumetric flow rate for all collecting cells.

Ter Veer et al.[9] studied the influence of initial liquid distribution in a column equipped with Raschig rings. They stripped a water/acetone solution with air. They assumed, starting from previous investigations, that packed column efficiency does not decrease, for high column to particle diameter ratios, if the initial distribution is well performed. So they deliberately maldistributed the liquid inlet into the experimental column in order to measure the effects of maldistribution on column efficiency. They found that the loading and flooding point are independent of the initial distribution, while under the loading point, maldistribution was lower than above. An increased flow close to the wall was detected above the loading point. They found also that a minimum number of distributing points per cross-section area is necessary in order to avoid maldistribution.

Pizzo et al.,[10] after their experiments, stated the importance of a good initial liquid distribution and the necessity to pay special attention to the distributor design. They also concluded that the packing "per se" does not promote good distribution and that the smaller the distance between the distributor and the packing, the better the initial distribution.

Hoek and co-workers[11] categorized liquid maldistribution as large scale and small scale ones. Large scale maldistribution develops along the wall due to the liquid tendency to accumulate on the column wall. In large diameter columns, this maldistribution cannot be easily compensated by radial mixing. Small scale maldistribution is related to liquid channeling, or rivulet formation, causing severe maldistribution on the particle scale. This causes a detrimental effect on the separation performance of the system that, however, is compensated by radial mixing. They proposed a diffusion model in order to evaluate the maldistribution along the column. Hoek et al. showed that the quality of initial distribution greatly affects the packing efficiency. They performed also experiments with structured packings, demonstrating that liquid distribution in these systems is quite uniform over a wide range of liquid and gas flows. However, noticeable liquid maldistribution may exist in structured packings at high gas flow rates. The channeling effect in this case is not severe, and radial mixing is large.

In 1991, Semkov[12] proposed a mathematical model of liquid distribution in a packing wetted by a multipoint distributor. The work is completely theoretical, and no comparison with experimental data is performed in order to prove its reliability. Semkov reports that the most used way to ensure liquid uniformity in practice is to use multipoint liquid distributors. This solution however does not ensure a uniform distribution so that a part of the bed is necessary for distributing the flow. The model is then aimed at the optimization of the height of the redistributing bed section which is necessary to obtain flow uniformity.

Kouri and Sohlo[13,14] studied large scale liquid and gas flow patterns in a column equipped with plastic pall rings and ceramic intalox saddles and fed with air and water. They put attention on studying the development of liquid wall flow and the effect of the interaction between gas and liquid. Particularly, they found a positive effect on liquid distribution connected to increased gas flow, observing also a more uniform distribution of liquid in conditions close to column loading. Liquid spreading is increased by increasing the gas load. By means of their experiments, they definitively stated that once the liquid and gas become segregated, the segregation tends to persist. Maldistribution of one of the phases causes maldistribution inside the other, and this effect becomes more and more pronounced in packings that provide a lower pressure drop, particularly in structured packings. These results emphasize the need of a careful design of the liquid and gas distributors. They also studied the effect of a poor liquid distribution and found that the gas maldistribution is affected by gas and liquid flow rates to a greater extent, and by type and size of packing to a lesser extent. Kouri and Sohlo used annular sampling sections to collect the liquid at the bottom of the packing and proposed to evaluate the maldistribution factor, Mf, already defined by Hoek, by using the velocities instead of the volumetric flows:

$$\mathrm{Mf} = \left[\sum_i \frac{A_i}{A}\left(1 - \frac{u_i}{u_{\mathrm{av}}}\right)^2\right]^{0.5} \tag{2}$$

where A_i is the area of the ith annular section, A is the area of the column cross-section, u_i is the liquid velocity over the ith annular section, and u_{av} is the mean liquid velocity over the column cross-section. When the liquid flow distribution is uniform, Mf is zero.

Ibrahim[15] reported an experimental study on liquid distribution in a column equipped with pall rings and operated with air/water streams. The column was in Perpex and was operated over a wide range of air and water flows. Experiments with different packing heights were performed. Ibrahim found that the establishment of equilibrium liquid flow conditions requires a depth of packing equal to 2.5 times the column diameter and that the initial distribution supplied by the distributor was not maintained under all conditions due to disturbances generated by the initial layers of the packing. This confirms what stated by Albright[2] regarding the "natural" distribution of the liquid inside the packing.

Marchot et al.[7] discussed deeply the problem of maldistribution. They proposed a statistical model of the liquid flow to analyze experimental results obtained by X-ray computed tomography. The model was developed on the scale of the size of an elementary cell where the bed can be considered homogeneous and isotropic (this scale is lower than the particle size). The liquid flow was modeled by assuming a network of these cells constituting the volume of the bed. The liquid flow is assumed to have an equal probability of repartition among the cells in order to maximize the entropy and leading to the equilibrium distribution. Due to geometrical reasons, only a fraction $\langle \varepsilon_s \rangle$ of the cells are accessible to the liquid (for instance, because of plugging or the particular arrangement of the packing elements or initial distribution). A nonirrigated cell may occur because it is not statistically accessible or accessible and not irrigated. The fraction of irrigated cells can then be evaluated by the following expression:

$$\langle f_w \rangle = \frac{\langle u_L \rangle_\infty}{\langle \varepsilon_s \rangle u_m + \langle u_L \rangle_\infty} \tag{3}$$

where u_m is the minimum irrigation flow rate and $\langle u_L \rangle_\infty$ is the liquid superficial velocity averaged over the whole cross-section. A theoretical maldistribution factor has been derived on the cell scale:

$$\mathrm{Mf} = \frac{2 - \langle \varepsilon_s \rangle}{\langle \varepsilon_s \rangle} + \frac{u_m}{\langle u_L \rangle_\infty} \tag{4}$$

This factor shows that maldistribution decreases with the flow rate and with the statistic accessibility.

Finally, Sun et al.[16] proposed a model for the simulation of maldistribution in random packed columns. They compared the model also with experimental data showing a good agreement. They discussed the previous models proposed by Scott,[17] Tour and Lerman,[18] Dutkai and Ruckenstein,[19] Hoek et al.,[11] Cihla and Schmidt,[20] and Onda et al.[21] Scott[17] and Tour and Lerman[18] used the concept of random walk, considering the liquid distribution as caused by a succession of random movements on the packing particle scale. If the number of steps of a random walk is large, the probability distribution is given by the diffusion equation, so they adopted a diffusion-like equation to describe the liquid movements. So a radial dispersion coefficient D was introduced. The following research[11,19−21] was than related to the use of a diffusion model. The random walk model is based on the assumption that liquid distribution obeys a Gaussian probability distribution. This model cannot predict wall flow or the flow with a distribution different from a centered liquid distribution at a low flow rate. Moreover, the diffusion model requires the evaluation of an empirical parameter, called the spreading coefficient, deduced by means of experiments. It was also demonstrated by Bemer and Zuiderweg[22] that experimental local flow rate deviates strongly from the flow rate predicted by the diffusion model. Sun at al. proposed a rigorous approach to the problem based on the averaged Navier−Stokes equation and on a constitutive equation for the evaluation of the dispersion coefficient of the volume fraction and turbulent dispersion in order to account for the liquid spreading in random dumped columns. Due to the mechanistic nature of the model, it can be used over a wide range of column sizes and operating conditions. They concluded from their simulations that the liquid spreading ability of a packing can have a significant effect on the buildup of wall flow and the development of liquid flow patterns toward its equilibrium maldistribution. The factors affecting liquid spreading are recognized to be the physical properties of the liquid, packing structure, and liquid flow rates. The experiments with poor initial liquid distribution also showed that a good initial distribution is fundamental for the optimal performance of the column operation. It can be observed that the important effect of gas flow rate variation over the liquid distribution is not taken into account in this paper (constant gas flow rates are used in the experiments).

2.2. Structured Packings. Structured packings are conceived in order to maintain flow configuration along the bed, so if a good distribution of the liquid and gas flows is realized, it will be maintained for a longer bed length than in the case of random packings. Compared to random packing, they do not present severe channeling problems and have a reduced pressure drop and a largely enhanced surface to volume ratio. In comparison with random packings, structured packings require a better inlet distribution of gas and liquid. Stikkelmann et al.[23] studied the gas and liquid distribution in different types of structured packings. Provided that a correctly designed liquid distributor is employed, they concluded that, below the loading point, the liquid flow is not influenced by the gas, and liquid maldistribution increases only with low liquid loadings. Close to loading conditions, liquid maldistribution rapidly increases accompanied by large scale liquid segregation. The gas has a negligible influence on liquid spreading. Finally, they discussed their results in terms of two parameters: the Mf, maldistribution factor (already discussed for random packings), and the Wf, wall factor (ratio of the flow rate in an annulus near the wall to the average flow rate, equal to 1 for an ideal distribution). Spekuljak and Monella[4] presented a new concept in liquid and gas flow distributors, based on irrigation by liquid films instead of liquid jets. They described 19 requirements for a good liquid distributor for structured packing systems. Edwards and co-workers[24] carried out a characterization of the maldistribution of liquid and gas flows. They performed tests by changing the distributor and artificially inducing the maldistribution of fluids. They demonstrated that the maldistribution is directly due to inlet flows and therefore can be defined as the deviation of the local velocity of the phase compared to the theoretical average velocity. They point out the importance of the depth of penetration of the maldistribution inside the bed and its impact on the column performance. Liquid maldistribution is described as related by both small scale effects due to the discrete drip point location of the liquid distributor as well as large length scale effects due to flow variations from drip point to drip point or across the distributor. Vapor flow, more continuous in nature, experiences only large scale effects related to geometry and location of the vapor feeds, collectors, and distributors. They proposed a measure of the depth of penetration of the maldistribution based on the approximate solution of the liquid and vapor transport equations. No comparisons of simulations with experimental data are performed. They found that the depth of the penetration of maldistribution is a strong function of the inlet distribution, emphasizing, once again, the importance of a well-designed distributor.

Fitz et al.,[25] studied controlled maldistribution on structured packings. These authors used a cyclohexane/*n*-heptane system at atmospheric pressure in a 1.2 m diameter column equipped with a Mellapak 250Y. The bed was 3.78 m high. Their results indicate that structured packing is less sensitive to under-irrigation of the wall zone with respect to random dumped packings; however their results are more sensitive to maldistribution. They measured a loss in efficiency by reducing the density of drip points.

More recently, Olujic et al.[26] analyzed the behavior of different high capacity packings with respect to the traditional packings. Different packs of Montz Pak B1-250 and Montz Pak B1-250 M (M stays for high capacity packing) are alternatively disposed with an angle of 90° to each other as in the industrial best practice. In their experiments, an air/water system is used. They studied the effect of the variation of gas and liquid flows and of the packing height on the liquid distribution quality.

Olujic and co-workers operated the column with the sole liquid flow rate; they analyzed the liquid distribution at the bottom of the column by means of a qualitative tomographic measure at different angles and heights of the column and used the coefficient of variation that is strictly related to the maldistribution factor used for random packings:

$$C_v = \left[\frac{1}{A_t}\sum_{i=1}^{N} A_i\left(\frac{u_i - \overline{u}}{\overline{u}}\right)^2\right]^{0.5} \text{ with } \overline{u} = \frac{1}{A_t}\sum_{i=1}^{N} A_i u_i \tag{5}$$

where $\overline{u}$ is the average velocity of the liquid in the column, u_i is the local velocity into a cell, A_t is the section of the column, A_i is the area of the single cell of the tomographic analysis, and N is the number of cells.

The coefficient of variation defines locally where the liquid has higher or smaller velocity compared to the average speed at a specific section of the column; the smaller the C_v, the more homogeneous the liquid distribution (boundary case: $C_v = 0$). However, this parameter does not give any idea about flow variation along the cross-section, so that Olujic at al. preferred to use the C_m coefficient proposed by Billingham and Lockett[27] that distinguishes between small and large scale maldistribution. The C_m is defined exactly in the same way as C_v, but $\overline{u}$ is replaced by $\overline{u}_i$ that is a local mean velocity defined as follows:

$$\overline{u}_i = \frac{\sum_{J=i}^{N} \delta_{ij}(A_i u_i + A_j u_j)}{\sum_{J=1}^{N} \delta_{ij}(A_i + A_j)} \tag{6}$$

where $\delta_{ij} = 1$ if i and j are neighbors and $\delta_{ij} = 0$ if i equals j or the cells do not share a common border. The ratio between C_v and C_m defines the maldistribution index MI, which depends on the grid size.

This parameter was used in order to compare the efficiency of the liquid distribution of the two packings. They found that a higher capacity system performed better than the conventional ones but at the expense of a higher wall flow. This is due to the fact that the different flow channels' geometry influences lateral spreading of the packings. In fact, they have a narrower channel in the upper inclined part which discourages the liquid to flow over the corrugation ridges and consequently reaching crossing points. Therefore, the liquid is moving toward the wall.

Spiegel[28] started to analyze the relation between the outflow of the distributor and the wetting condition of the packing immediately underneath it. He described different methodologies to assess the quality of the existing typologies of distributors (holes, tubes...). For example, one of the methods he reports is that of Moore–Rukovena,[5] where each drip point is the center of point circles that superimpose each other. The sum of the areas of the circles equals the column's cross section. The distributor quality is evaluated as D_0 by adopting the following expression:

$$D_0 = 0.4(100 - A) + 0.6B - 0.33(C - 7.5) \tag{7}$$

where A represents the packing cross-section not covered by the distributor and then not irrigated, B is chosen as 1/12 of the cross-section assumed to be the worst wetted, and C is the area twice wetted (overlap of point circles). A, B, and C are given as a percentage of column cross section. An explicating sketch is given in the paper of Spiegel. Such a relationship works fine for random packing systems combined with point distributors and uses only the geometrical layout of the distributor. No experimental evaluation of parameters is necessary. The correlation of Moore and Rukovena however is not applicable to line distributors, does not take into account linear liquid spread occurring in the first layer of structured packings, and behaves inconsistently for high drip point densities. Then, Spiegel defined a wetting index (WI) which depends on the geometry of the drip patterns but is independent of the specific outlet system, taking into account linear liquid spread and assuming a uniform flow from each drip point.[6,20,28] To use such an index, it is crucial to know the geometrical properties of the packing since it is necessary to know the ideal angle between the plane that passes through the set of drip points and the plane in the direction of the twist angle of the structured packing. As demonstrated by Spiegel, in certain WI applications, the following information is fundamental: the wetting angles, the number of the drip points, and the liquid flow rate. The calculation of the WI requires one to split the section of the packing in a grid: the higher the number of the wet cells of the grid, the larger the WI:

$$\text{WI} = \frac{\text{number of total wetcell}}{\text{number of total cells}} \tag{8}$$

In practice, the larger the WI (WI → 1), the more uniform the wetting; the smaller the WI (WI → 0), otherwise. The reference section for evaluating WI is indicated as the plane below one packing layer. The number of cells at the right and at the left of each drip point is given by the nominal corrugation angle of the packing, φ, from the packing element height, h, and from the hydraulic diameter, d_h:

$$n = \frac{h \tan(0.59\varphi)}{d_h} \tag{9}$$

In order to evaluate WI, the cross section is divided into square cells having the size of the hydraulic diameter. The cell directly below the drip point is marked with the right and left cells corresponding to n. WI is then evaluated from eq 8. The WI is as such accurate as many cells are used to develop the grid. About the fluid dynamic, if the WI is already large at the top of the packing, the wet portion of the whole packing is larger, and consequently, the overall efficiency of the column is higher. The measure of WI indicates a dependence of the distribution from the twist angle so that an optimization with respect to this parameter is possible. This last consideration corroborates the need to study, analyze, and optimize the fluid distributors for design and operation purposes and especially their interactions with the packed bed. The concept of WI is applicable also to random packing systems taking into account the two-dimensional lateral liquid spread. For WI < 0.25, a loss in separation efficiency is reported by Spiegel[28] which demonstrated a decrease in the number of theoretical stages per meter of about 30% by reducing the number of drip points and, then, decreasing liquid distribution.

The dependence of the WI on the more or less homogeneous distribution of the liquid entering the packing is also confirmed by Pavlenko et al.,[29] which used a completely different, but evenly effective, approach. Actually, Pavlenko et al. have studied the maldistribution of liquids by means of heterogeneous feeds in a column with freon. Their results show that the initial maldistribution, obtained by plugging one row of the point distributor, results in an increase of maldistriubtion along the packing (significantly decreasing separation efficiency). The development of maldistribution and of unwetted areas of the packing also depends on the layer rotation angle.

Other studies have been proposed for the liquid distribution of packed systems, although for different applications. Nevertheless, the studies in completely different areas and on other unit operations or reactors could sometimes have the effect of de-bottlenecking the problem of understanding phenomena for the packed columns also.

For instance, Alix and Raynal[30] have studied liquid distribution and liquid holdup in modern high capacity packing in order to model and optimize industrial gas/liquid contactors for postcombustion CO_2-capture plants. They adopted a gamma-ray tomographic system to obtain the liquid flow maps over a cross section of a 400 mm internal diameter column from which liquid holdup values can be deduced. They observed that the liquid flow is homogeneously distributed for both the random and structured packings, but with better results for the latter one.

Investigation of liquid maldistribution has been carried out for trickle-bed reactors also.[31,32] The reactor simulations by Atta et al.,[31] for example, suggest that for low liquid and gas velocities, the details of particle wetting phenomena seem to have a more significant effect in the case of a large diameter column rather than in a smaller diameter column. Also, they highlighted the effect of liquid flow on the quality of liquid distribution and indicated the need for liquid redistributors. Atta's model can be useful to establish the length in a column after which redistributors (and other internals like wall wipers) may be installed.

3. GAS DISTRIBUTION

Regarding the gas inlet flow, in general, the commercially available liquid distributors, specifically designed for structured packing columns, are based on an elementary concept accepted for several decades for random packings.[3] That is, the gas does not need additional redistribution, because the bed pressure drop acts by itself as a flow distributor.

However, the superior performances of the structured packings, if compared to the random ones, impose the requirements of a more elaborate solution for flow distributors in the packed columns. This is especially because, as introduced by Spekuljak and Monella,[4] the structured packing obeys the principle "maintain the flow configuration along the bed," which creates strong relations with the reciprocal inlet distributions of the liquid and gas flows.

Actually, the initial maldistribution is the key element for the modeling[13,33] and for the investigation of its effects on the pressure drops along the bed.[34]

Petrova et al.[33] have shown the possibility of using the dispersion model in order to describe gas distribution in packed columns, by also separating the estimation of the influence of the inlet device and the thickness of the packing layer on the gas flow irregularity. They demonstrated that, in the presence of more layers of different packing, it is possible to divide the column into several horizontal sections; in each case the redistribution capability of each section can be well-characterized by one parameter only, named the "redistribution coefficient," which is definitely dependent on the packing type.

It is worth underlining that the redistribution coefficient is totally different from the corresponding coefficient involved in the dispersion model of the liquid flow, which was proposed by Chila and Schmidt,[20] since the mechanisms of redistribution of gas and liquid are quite different.

A large-scale experimental study for establishing the relation between the quality of initial gas maldistribution and the hydraulics of a structured packing bed has been proposed by Olujic et al.[34] They studied dry and wet beds with an air/water Plexiglas column operating under ambient conditions. The system prepared for experimentations is particularly clever since the phenomena within the column are visible and the fluid used (freely available) does not present particular safety aspects. They provided data and relationships to design the bed height needed to smooth out some aspects of initial maldistribution. Corroborating certain prior theories, it appeared that the severity of initial gas maldistribution influences the pressure drop of the bed. Gas maldistribution is influenced by liquid distribution. Structured packings having a perforated surface area ensure maximal lateral transport of gas within the packing layer.

Notwithstanding the importance of good gas distribution and its obvious relation with good liquid distribution, a usual mistake in the revamping process of packed columns is the lack of a specific gas distributor. The assumption that the gas flow is spontaneously distributed itself in the packing bed has led to some troubles in revamped columns (see for example Kurtz et al.[35]). When a gas maldistribution occurs, relevant consequences in mass transfer efficiency are certified by a long time.[36]

4. PERFORMANCE ASSESSMENT

It is now clear how gas and liquid mutual distribution plays a fundamental role in the efficient operation of a packed column. Poor distributions reduce the effective wet packing, and from a practical point of view, they lead to reduced performances due to poor gas−liquid contact efficiency and to reduced effective interfacial area for mass transfer, imposing a higher HETP to match the expected performances.[5,6,37]

One of the key points of scientific and technological interest is the assessment of the performances of the packed columns, and several promising methods have been developed for such a purpose.

Traditionally, the maldistribution of gas and liquid flows in the packed columns has been characterized using the coefficient of variation or the ratio of maximum to minimum superficial velocity into the packing. According to Edwards et al.,[24] these provide some useful insight into the severity of maldistribution introduced into a bed by the liquid distributors and gas feeds, but they are not necessarily reasonable indicators of the depth of penetration of the maldistribution into the packed bed and, therefore, of the impact of such a maldistribution on the packed column performances. People from BOC Gases Technology gave an interesting definition of the maldistribution depth of penetration: "the depth into the packing over which the coefficient of variation exceeds a design limit."

A corrugation geometry based model has been proposed by Olujic et al.[37] to improve the efficiency of structured distillation packing through a better exploitation of the available phase separating potential. Agreeing with the authors, the current unexploited potentialities are mainly due to a rather superficial approach to the modeling and prediction of the packing performance and to a significant lack of experimental data able to highlight certain phenomena.

This is the reason why research activity has been devoted to performing experiments on a pilot plant in order to better understand the problem of interaction between the distributor and the area beneath the packing layer, also with respect to the arrangement of liquid and gas flows inside the packing resulting from this interaction. The discussion about these findings will be reported in a companion paper.

It is worth underlining that several studies are focused on the development of different configurations of the drip points of liquid distributors. Actually, since it is now clear that the liquid distributors cannot be underestimated any longer and that they are a key component for the optimal performance of packed distillation columns, their design is commonly based on the drip point density. Nevertheless, certain novel geometries have been proposed with promising performances. For example, the modern baffle plate distributors by Sulzer Chemtech have the liquid delivered to the packing in the form of drip lines rather than drip points. Although the WI, which is the ratio of wetted to total geometrical surface, is still used as a quantitative measure to describe distributor performance, it is important to compare different distributor systems, e.g., those with conventional drip points, those with drip lines, and the hybrid intermediate solutions. Also in this case, the WI depends on the geometry of the outlet system, the orientation of the distributor with respect to the packing, and the geometry of the packed bed, and thus, it provides an assessment of the distribution quality of the combination of liquid distributor and packing. Spiegel[28] has demonstrated that the WI is significantly higher for line distributors than for point distributors despite the lower number of outlet zones. According to him, the available information on lateral liquid spreading in structured packing in the open literature is scarce. A companion paper will be aimed at trying to bridge this gap.

5. THE PROBLEM OF DROPLETS FORMATION

In the assessment of packed column efficiency, the theories of falling jets and films and the generation of droplets play a fundamental role, and both of them deserve at least a short overview. Actually, several phenomena have to be mentioned since all of them can contribute, more or less, to the entrainment and loading of the column, sometimes leading to the flooding condition.

Briefly, these phenomena are related to the kind of liquid jet outflowing the drip points of the liquid distributor, which can

- preserve its structure (stability) until it achieves the packing
- present the Rayleigh−Plateau instability
- generate droplets, the splashing of which gives place to entrainment
- although stable, generate droplets in the splashing against the packing

but also to the falling film laying on the packing surface, which can

- flow in the gravity direction
- be entrained partially or totally by the gas flow up to the loading and flooding condition
- generate waves and, next, droplets and entrainment

Regarding the falling jets and films, as far as the length increases, the jet loses its ideally cylindrical shape, generates larger and larger waves, and decomposes into a series of droplets, as observed and explained by Plateau−Rayleigh. Such a deformation can be basically characterized by a set of sinusoidal functions.[38,39]

More difficult is the characterization of phenomena governing the droplet impact over the solid surface and consequent interactions. They have been investigated in depth by many authors, and several reviews of the subject are already available, to which we point the reader for more details.[40−42] The need to predict the phenomena that occur at the splashing of a droplet is so great that both theoretical and numerical routes have been taken. The splashing of a single droplet, on a wet or dry surface, can generate a number of smaller droplets, which can have the effect of increasing the entrainment.

The theoretical studies of droplet and solid surface interaction started with the analysis of the impact of a single droplet. Roisman et al.[43] proposed a theory for the liquid droplet on a dry surface where the effect of the splash depends on the surface tension of the liquid, the diameter of the droplet, and the impact velocity. The theory was subsequently extended to the case of wet surfaces, to two droplets,[44,45] and next, to multiple droplets with many numerical solutions of the problem (finite-volumes methods).[46,47]

Unfortunately, the fluid flow associated with impinging droplets is rather complicated and not yet fully understood. Various phenomena can occur when a droplet impacts a surface, and the outcome depends on the droplet and surface properties. As reported by Sikalo and Ganic,[45] the number of independent parameters governing the process can be reduced to a set of dimensionless groups, where one of the most important is the so-called impact Weber number:

$$We = \rho v D^2/\sigma \qquad (10)$$

with ρ being the liquid density, σ the liquid surface tension, D the droplet diameter, and v the impact velocity. Nevertheless, such a number is not sufficient alone to describe the phenomena of droplet impact. Thus, other studies have been proposed in the literature to deepen the detail of characterization of droplet splashing. Specifically, Durikovich and Varland[48] classified two families of phenomena: bouncing, when the Weber number is small, and splashing, when the

Weber number is large. They examined experimentally the boundary between these two families. Cossali and co-workers[49] extended the characterization by means of the Ohnesorge, Bond, Reynolds, and Froude numbers in order to separate the effects of kinetic energy and liquid viscosity. In their work, a photographic documentation is annexed to clarify the splash dynamics and morphology.

6. DESIGN DIRECTIVES FOR LABORATORY/PILOT PLANTS

Several pieces of small scale equipment have been described in the literature. Some of them were using special compounds, such as the freon packed column of Pavlenko et al.[29] or the butanol/water packed column of Pizzo et al.,[10] since they are strictly related to the special application to be studied. Conversely, other equipment uses air and water as inlet flows; such pilot plants have been set up looking at the simplest solution in terms of installation costs and safety problems. This is a reasonable solution whenever the experiments are mainly dedicated to the study of system fluid-dynamics. The works by Stikkelman et al.,[6,23] Ibrahim,[15] and Olujic et al.[26,34] can be mentioned for the air/water system.

Stikkelman[6] has analyzed several aspects of the liquid−gas contact in a pilot structured packing column. The gas and liquid distribution is analyzed, and the optimal conditions are provided for different kinds of packings in terms of flow rate, twist angle, packing geometry, HETP, and HETP/diameter ratio. Stikkelman's work is an important reference for the planning of experimental campaigns since the variations of the maldistribution parameters and indices are clearly stated and the related issues highlighted, although a direct relationship between the distribution and the packed column efficiency is still missing.

Ibrahim[15] proposes a good description of the unit and instrumentation used to set up the packed column. Although the random packing is used (Pall Rings), devices, measurements, and instrumentation positions can be adopted also in the case of structured packing, especially if the interest is focused on liquid distribution. Degrees of freedom of the sensitivity analysis are the liquid flow rate, drip point geometry, HETP, and the distance between the distributor and packed bed. A multiple vessel to collect the outlet liquid from the bed is placed at the bottom of the column. The outflow distribution is measured by using the levels of the liquid within each single area. In addition, the distribution of the liquid is also cross-checked with the single flow rate of the pipe that receives the outflow of each zone of the packing.

Olujic et al.[34] have built and operated a large scale air/water plant to observe the effects of variation in gas and liquid loads and packed height on the liquid distribution quality of a high capacity corrugated sheet structured packing (Montz Pak B1-250M). Their work is quite important to assess in advance, for example in the preliminary industrial design phase, the possible critical conditions, and limit situations. For instance, they operated a column with 1.4 m of internal diameter consisting of a number of flanged Plexiglas sections. The Plexiglas part of the column is supported by a stainless steel column sump, where a gas inlet distributor is accommodated to distribute air by means of a powerful, electronically controlled blower. Instrumentation, control loops, and electronic devices described in this work are the same as those adopted in industrial applications. The experimental setup used by Olujic et al. gives fundamental guidelines to set up units and instrumentation for laboratory and pilot-scale analysis: 152 drip points for the liquid distribution, which corresponds to 100 wp/m^2; the liquid flow rate reaches 43 m^3/(m^2 h); up to 6 m of packing can be installed; a special collector with several compartments is installed at the bottom of the column to collect the liquid coming from the structured packing and to allow the analysis of the liquid distribution. An air blower with 8 m^3/s as a maximum potentiality is used for the inlet air flow rate.

Pavlenko and co-workers[29] performed experimentations on a similar scale, adopting a packed column with an internal diameter of 0.9 m.

7. CONCLUSIONS

This overview reports the state-of-the-art of what has been already investigated and what is still to be done in the field of liquid distributors. If the literature is quite extensive for the assessment and optimization of the packings, it is not the same for distributors mainly in relation to the interactions among distributor and beneath packing. Thus, this review of the literature and pilot-scale plants has emphasized the need to understand the relationship between the configuration of the gravity distributors and the column efficiency, mainly in the case of structured packing systems. The effect of the following parameters has to be clarified:

1. Inlet liquid flow rate
2. Inlet gas flow rate
3. Liquid/gas flow rate ratio
4. Distributor geometry (different number/disposition/shape of drip points)
5. Twist angle
6. Distance between distributor and packing

Notwithstanding the reliability of models, the following points are even important before starting the experiments:

7. Hydraulic tests are needed on the distributor to check its functionality and effectiveness
8. Test the distributor and column conditions under turndown, overcapacity, and flooding conditions
9. The measures of humidity at the top of the column are needed to provide mass transfer information under different operating conditions of the packed columns

A following paper will be devoted to the pilot-scale column design and experimental campaign, and finally, to the experimental data analysis and modeling of entrainment and optimal design of the liquid distributor.

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Notes

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