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WELCHEM
PROCESS TECHNOLOGY

How to...
RANDOM PACKINGS

How to design and calculate Random Packings

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How to calculate hydraulics of Random Packings

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Random Packings ("Rings") are universal all-rounders: they are not expensive, have good separation performance, low pressure drop, adapt to the column diameter and are available in many sizes, types and materials. They have been in technical use for more than 100 years.

A Random Packing is a volume of dumped hardware where the liquid is wetting the hardware and in this way provides a mass transfer area (*Fig. 1*).

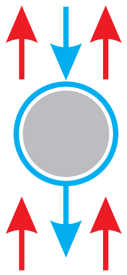

Fig. 1: Principle of Random Packings

This principle is well known since hundreds of years. Brushwood tufts were used to concentrate brine and were piled up in so-called graduation houses and sprinkled with brine. The water evaporates and the brine concentrates, reducing the amount of fire wood needed to vaporize the brine. Random Packings were therefore already successfully used for mass transfer and energy saving 500 years ago!

The technical development of Random Packings started with the patent of Fritz Raschig in 1915. He defined a cylindric ring with equivalent height and diameter (*Fig. 2*). By this the classical „Raschig Ring" was born and – probably – since this time Random Packings are also called „rings".

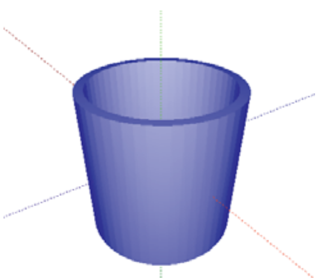

Fig. 2: Basic Raschig Ring

In the last 100 years several new types of packings were invented, tested and came in use. Roughly estimated, there are about 200 Random Packings, taking into account the material classes (ceramic, metal, plastic) and the different sizes and shapes.

One can classify the Random Packings based on the basic geometry of the packing element as well as its type of shell surfaces.

The development can be classified in so-called „generations". The first generation is represented by the patent of Fritz Raschig: the shell of the basic geometry (in case of the classic Raschig Ring the cylinder) is solid. In this case the pressure drop of a packing element is very dependent on its orientation. If the axis of the cylinder is perpendicular to the gas flow, the body blocks the gas flow. If its axis is in flow direction, the body acts like a pipe and has almost no pressure drop.

In order to reduce this positional dependency and to reduce the pressure drop of the entire packing bed, the shell surface of the packing elements was designed with openings in the 2nd generation.

In the 3rd generation, this development was then continued and the shell surfaces were reduced to web surfaces and the inner volume of the body was provided with additional surfaces.

While in the first generation the liquid formed a film by flowing over the surface, the 3rd generation also relies on the formation of droplets and their contribution to mass transfer.

Some suppliers advertise 4th and even 5th generation Random Packings. Whether the features implemented in these types of packing justify the definition of a new generation is questionable.

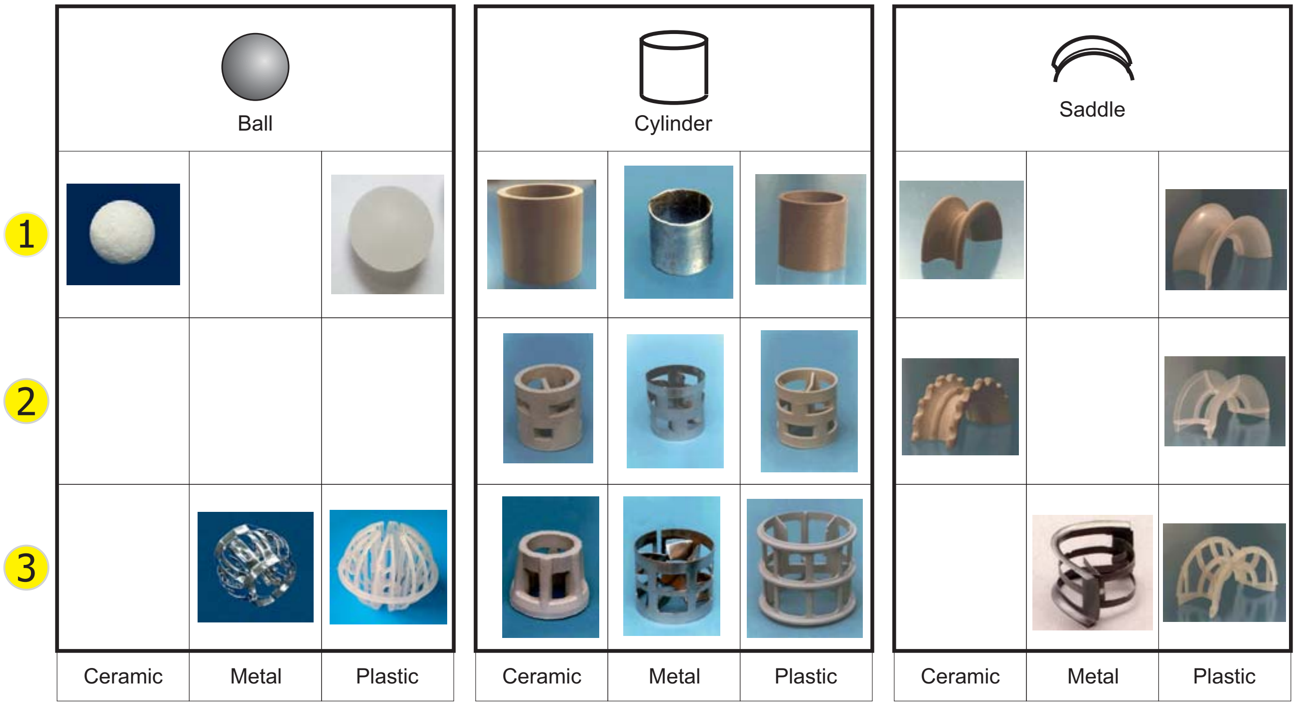

Fig. 3: Generations of Random Packings development

Fig. 3 shows a survey of the variation of the three basic geometries „ball“, „cylinder“ and „saddle“ in the three generations. The table is filled with pictures of corresponding representatives. Since there are restrictions regarding the formability of the respective materials, not all cells of the table are occupied.

In the past 20 years some high capacity rings were presented. Their basic geometry is a block (cuboid). The latest development of Random Packings came from Raschig by the patented Raschig Super Ring Plus. Actual this is the high end packing for maximum capacity. The work horse of the metal packings is still the saddle and a still often used packing type is the Pall ring (2nd generation clylindrical ring).

All Random Packings are basically described by their specific geometrical surface area (a_{geo}) and void fraction ε. The shape of the packing elements can be characterized by the dry pressure drop. All this data is normally provided by the packing supplier.

The qualitative pressure drop characteristic of a counter-current two-phase flow through a packed bed is shown in *Fig. 4*: In the double-logarithmic scaled diagram the pressure drop is

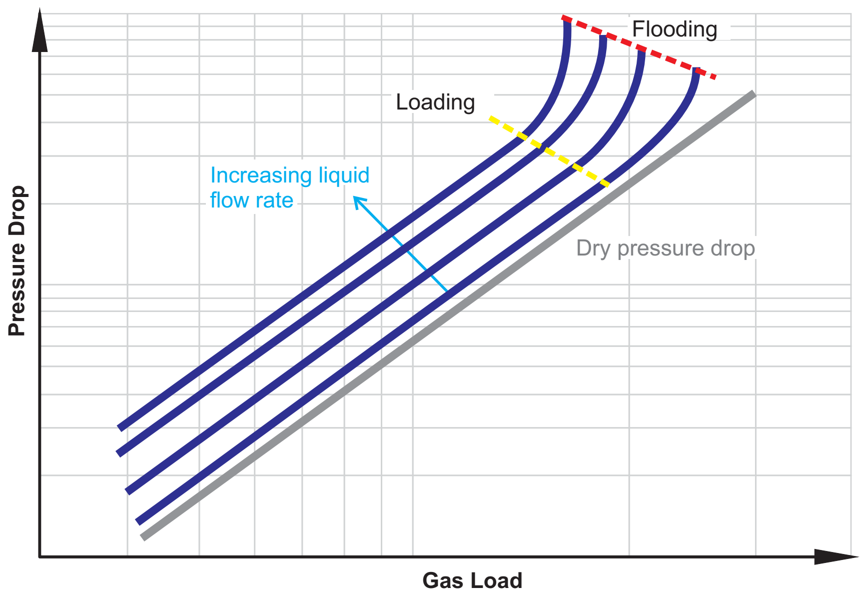

Fig. 4: Qualitative hydraulic characteristic of Random Packings

a straight line, where liquid and gas can pass each other without hydraulic interaction.

By increasing gas load there is the so-called *loading*, where liquid is accumulated by the counter-current gas: liquid holdup rises and the pressure drop increases disproportionately. This interaction between gas and liquid is conducive for mass transfer conditions.

By further increase of gas load, the liquid is accumulated to such an extent that a liquid layer is formed and the gas becomes disperse phase. The liquid flow rate through the bed is thus reduced, flooding occurs. The pressure drop of the bed also increases drastically. At this flooding point, the counter- current of the phases breaks down.

MODEL STRUCTURE

To predict the hydraulics of Random Packings, we have to use a suitable model structure to transfer the complexity and randomness of the dumped bed and its effects on the flow of liquid and gas.

The idea of a model is to reduce complexity to structures whose calculation is possible and known. The better a model is suited for the description, the fewer fitting parameters are necessary.

There are a variety of models that have been developed over the last 100 years. However, many of them are purely empirical, graphical or built on several fitting parameters that can only be determined experimentally. Thus, these models are not necessarily applicable for newly developed or non-measured types.

Therefore, the use of model-based approaches is strongly recommended.

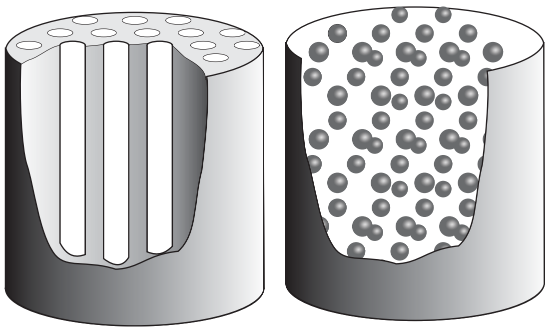

Fig. 5: Model structure „Channel“ and „Particle“

To model the structure of Random Packings, two structures are mainly used (*Fig. 5*). One is based on parallel channels, the other on particles. Both models transfer Random Packings to a regular structure, which can be calculated by basic principles. In case of the „Channel model“ one can use the pipe flow calculation, for the „Particle model“ the investigations of fluidized beds can be used.

In both model structures the Random Packings are transferred to a model based on the same surface area as well as the same hardware volume: In the Channel model to a certain number and diameter of the channels, in the Particle models to a certain number and diameter of particles.

In the first step, the models are validated by calculating the *dry pressure drop*. In the next step, the *liquid holdup* is implemented in the model structure and its impact on the calculation has to show up the hydraulic behavior of Random Packings.

HOLDUP

The liquid holdup is normally expressed as a relative value based on the tower volume:

$$h_L = \frac{V_L}{V} \qquad (1)$$

The liquid holdup and its change with increasing liquid and gas load is the driving force of the hydraulic behavior of Random Packings.

Fig. 7 shows qualitatively liquid holdup vs. gas load for various liquid loads in a double-logarithmic diagram. The liquid holdup stays almost constant for a certain liquid load till at the loading point it starts increasing.

When shutting down the liquid, not all liquid will leave the Random Packings. Due to capillary forces and structurally reasons, some liquid will stay within the bed. This part of the liquid holdup is called *„static holdup“* (*Fig. 6*). The total holdup during operation is therefore the sum of this static holdup and the so-called *„dynamic holdup“*:

$$h_{L,tot} = h_{L,static} + h_{L,dyn} \qquad (2)$$

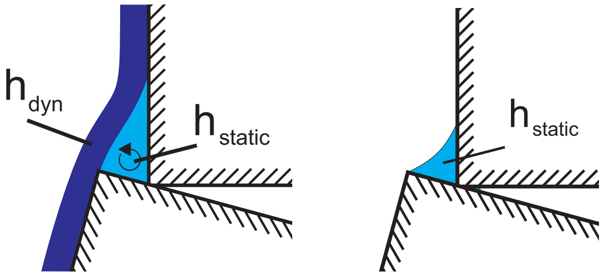

Fig. 6: Parts of liquid holdup

According to ENGEL 1999 the static holdup can be calculated by:

$$h_{L,static} = 0.333 \cdot \exp\left(-0.22 \cdot \frac{g \cdot \rho_L}{\sigma \cdot a_{geo}^2}\right) \quad (3)$$

To calculate the dynamic liquid holdup below the loading h_{dyn0}, *eq. (4)* can be applied:

$$h_{dyn0} = 3.6 \left(\frac{u_L^2 \cdot a_{geo}}{g}\right)^{0.33} \left(\frac{\eta_L^2 \cdot a_{geo}^3}{\rho_L^2 \cdot g}\right)^{0.125} \left(\frac{\sigma \cdot a_{geo}^2}{\rho_L \cdot g}\right)^{0.1} \quad (4)$$

To properly account for the liquid holdup above the loading h_{dyn}, the pressure drop of the packing must be included in the calculation. This leads to an iterative process in calculation, since the pressure drop is a function of the liquid holdup as well:

$$h_{dyn} = h_{dyn0} \cdot \left[1 + 36 \cdot \left(\frac{\Delta p_{irr}}{H \cdot \rho_L \cdot g}\right)^2\right] \quad (5)$$

PRESSURE DROP

The basic equation for the dry pressure drop of Random Packings can be written as *eq. (6)*. It describes a line within a double-logarithmic scaled diagram.

$$\frac{\Delta p_{dry}}{H} = 10^n \cdot F^m \quad (6)$$

By modeling Random Packings by the particle structure, the pressure drop correlation of a fluidized bed can be used [STICHLMAIR 1989]:

$$\frac{\Delta p_{dry}}{H} = \frac{1}{8} \cdot \zeta_0 \cdot a_{geo} \cdot \frac{\rho_G \cdot u_G^2}{\varepsilon^{4,65}} \quad (7)$$

To account for the liquid component in the particle structure, the liquid holdup is superimposed as particle structure (*Fig. 8*).

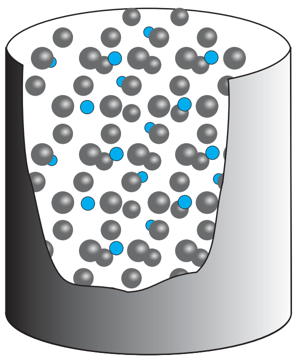

Fig. 8: Liquid holdup in Particle model

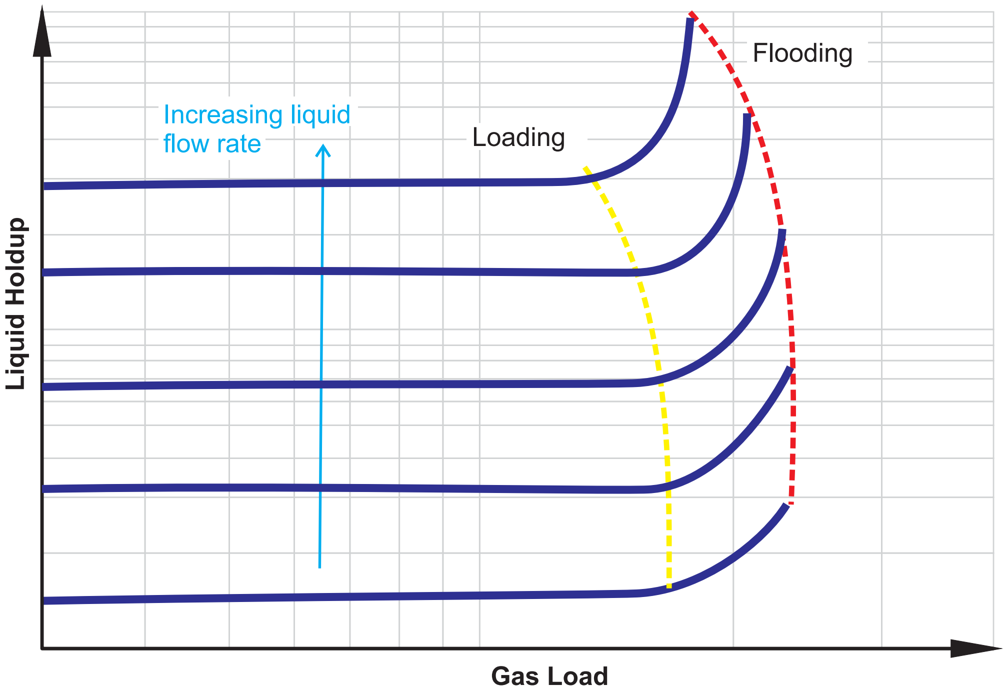

Fig. 7: Qualitative characteristic of liquid holdup

The liquid reduces the void fraction of the packing and enlarges the geometric area of the packing. Both effects are invoked in the pressure drop correlation:

$$\frac{\Delta p_{tot}}{H} = \frac{1}{8} \cdot \zeta_0 \cdot (a_{geo} + a_L) \cdot \frac{\rho_G \cdot u_G^2}{(\varepsilon - h_{dyn})^{4,65}} \quad (8)$$

The liquid area contributed by the liquid holdup can be calculated by *eq. (9)*.

$$a_L = \frac{6 \cdot h_{dyn}}{d_L} \quad (9)$$

By *eq. (1)* to *eq. (9)* one can calculate the total pressure as well as the liquid holdup of Random Packings. As input parameters the geometric area, the void fraction and the dry pressure drop of the packings are needed – no additional packing-individual fitted parameters!

FLOODING

To prepare the flooding calculations, *eq. (7)* and *eq. (8)* can be written as *eq. (10)*:

$$\frac{\Delta p_{tot}/H}{\Delta p_{dry}/H} = \frac{a_{geo} + a_L}{a_{geo}} \cdot \left(\frac{\varepsilon}{\varepsilon - h_{dyn}}\right)^{4,65} \quad (10)$$

From the mathematical point of view, the slope of the pressure drop characteristics at flooding conditions tends to be infinity:

$$\left.\frac{\partial\, \Delta p_{tot}/H}{\partial \Delta p_{dry}/H}\right|_{Flooding} = \infty \quad (11)$$

The reciprocal representation of *eq. (11)* can be used to evaluate the flooding factor:

$$\left.\frac{\partial \Delta p_{dry}/H}{\partial\, \Delta p_{tot}/H}\right|_{Flooding} = 0 \quad (12)$$

There is an explicit numerical solution of this *eq. (12)* in ENGEL 1999. Therefore it is possible to calculate an operation diagram as qualitatively shown in *Fig. 9* quite fast.

Beside the loading and flooding curve for the packing, one can add the system flood characteristics as an additional limit.

A design load should be at loading conditions for good mass transfer.

MALDISTRIBUTION

When liquid flows as a trickle through a packed bed, the liquid follows gravity but constantly changes its direction. This effect is partly random and dependent on the installation effects (therefore the packing is called *Random* Packing) and partly intrinsic due to the shape of the packing element.

In result, liquid can accumulate locally (e.g. in hotspots within the packing and at the tower shell). This effect is called maldistribution.

Even though the „mal-“ suggests a negative effect, maldistribution helps to evenly wet a bulk: starting from the liquid feed points, the liquid is distributed within the bulk. However,

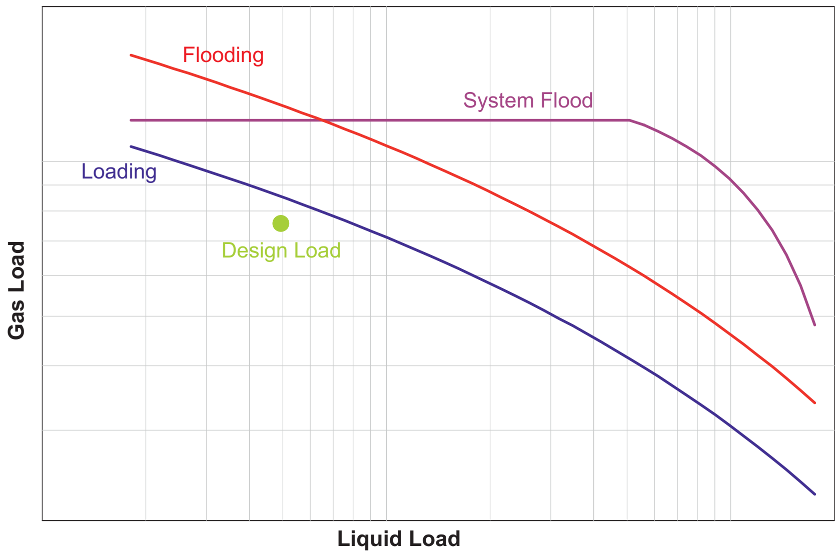

Fig. 9: Operation diagram

the same effect leads to uneven distributions in the liquid after a certain packing height. This worsens the conditions for mass transfer.

To make up for this effect, the only thing left to do is to collect and redistribute the liquid.

To quantify the maldistribution effect, WELCHEM presented 2007 a cell model approach. The packing volume is modeled as a hexagonal cell volume (each cell represents a single Random Packing element). Each cell has individual information of its behavior concerning the transfer of liquid to neighboring cells (*Fig. 10*).

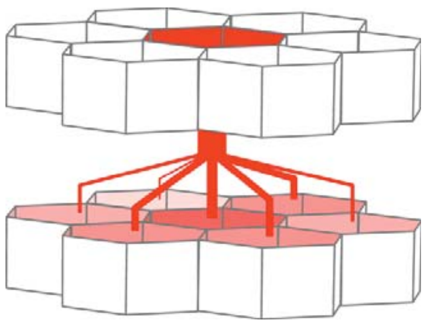

Fig. 10: Cell model for maldistribution

These parameters (called dispersion coefficients) are evaluated for each packing type. Because of the huge variety of shapes and sizes, this is not done by physical experiment, but by evaluation of 3D models of the packing elements. It is called „virtual irrigation“ and determines the deflection of streamlets into neighboring cells based on the orientation of the packing element within the cell (*Fig. 11*).

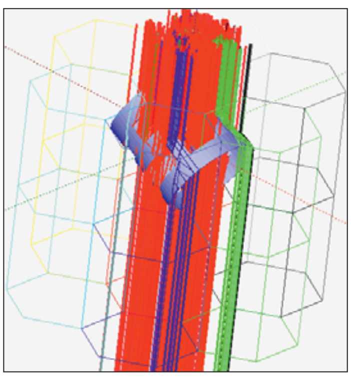

Fig. 11: Virtual irrigation of 3D packing element

In order to model the effects of the gas counter-current and its impact on the liquid distribution, an extensive measurement program was performed at the Technical University of Munich [HANUSCH ET. AL 2017]. Based on these results, a very good agreement with the experiments could be obtained by modeling local hydraulics in a cell based on the equations presented in *eq. (1)* to *eq. (9)*.

The presented maldistribution model is implemented in the software TRAYHEART. Its database contains hundreds of packing elements and a large number of RandomPackings with these dispersion coefficients.

In the software the maldistribution calculation is connected to the layout of distributors. By this one can predict the development of maldistribution along the liquid run length of a packing for a certain load (gas and liquid!). *Fig. 12* shows an example of a 50mm metal saddle with an initial distribution by a trough distributor.

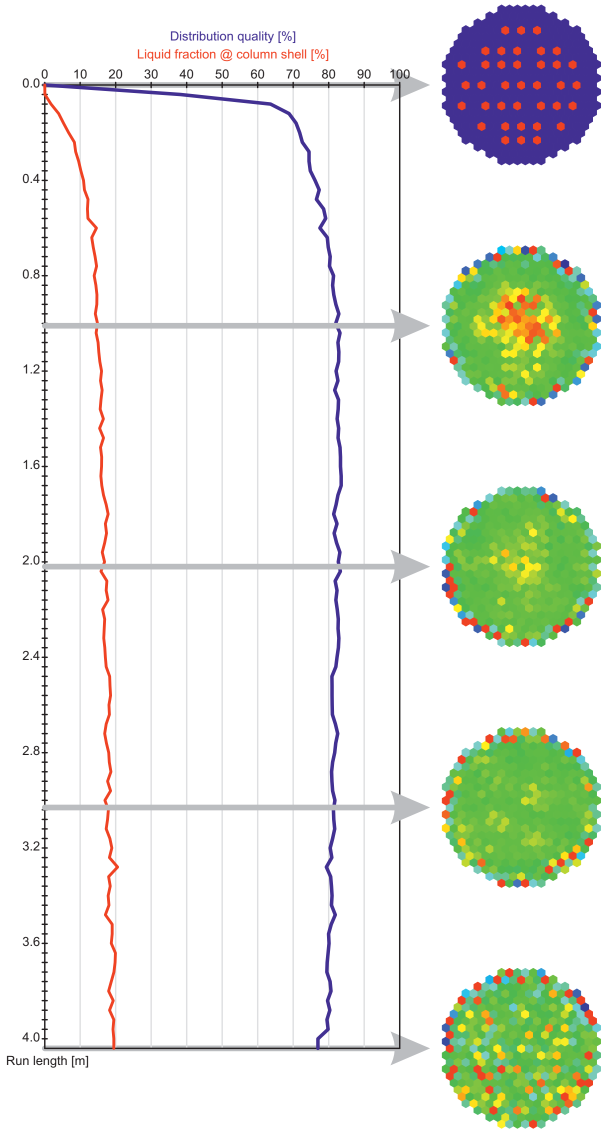

Fig. 12: Distribution quality vs. run length

By a detailed evaluation of this maldistribution one can determine criteria for the need of redistribution and the best interaction of initial distribution and Random Packings.

FILLING OF BEDS

To fill a certain volume with Random Packings, the supplier has to deliver the right quantity. This sounds easy — but it is not that easy to agree on the same volume: The supplier has counted the packing elements within a reference volume. But only for the diameter of this standard cylinder the specified number of pieces and thus the specific weight applies. If the packing is used in a different column diameter, the ordered volume must be adjusted. For this reason, all suppliers provide so-called „volume decrease curves“ to calculate the correct volume to fill a certain column volume.

Another effect of Random Packings is „settling“: Depending on the shape of the packing, the bed may settle during operation. Due to thermal and mechanical influences, packed beds arrange themselves in an optimized manner and thus take up less volume. The more the packings interlock, the less settling losses there are. The smoother the outer surfaces of the packing, the greater the settling losses (up to 10%).

Conclusion

Random Packings offer good options for normal pressure and high pressure applications due to their moderate pressure drop, reasonable prices, and the large variety of material, shape and size. They are comparable easy to calculate. General, reliable models are available.

The efficiency of Random Packings is closely connected to the quality of initial liquid distribution and maldistribution effects.

About the author

Volker Engel studied process engineering at the Technical University of Munich and did his Ph.D. thesis on packed columns with Prof. Johann G. Stichlmair. Since 1998 he has been the managing director of WelChem Process Technology GmbH and head of the TrayHeart software. TrayHeart has developed into the state-of-the-art design tool for trays and internals in process technology.

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