

# **DISTILLATION COLUMNS WITH STRUCTURED PACKINGS IN THE NEXT DECADE**

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## **ABSTRACT**

The analysis of the history of structured packings allows the conclusion that the innovation cycle will become faster.

Based on the separation power as an alternative way to represent the performance characteristics an estimate of the next level of what might be the ultimate separation power is given.

Regarding the column internals like distributors only slight improvements are expected, typically in form of streamlined forms and cheaper manufacturing.

CFD and computer tomography as tools to better understand the complicated two-phase flow processes in distillation equipment will be of great importance for the development of new designs.

A general trend is the emerging of multifunctional packings and their application in combined systems, like catalytic distillation or dividing wall column.

## **INTRODUCTION**

A few years ago the U.S. Department of Energy and the American Institute of Chemical Engineers initiated several workshops together with about 150 experts from industry and universities with the task to identify the technical barriers, the research needs and the priorities of the chemical industry regarding separation processes. This resulted in the U.S.-Initiative Vision 2020 with the goal to win a leading role of U.S. chemical industry by 2020 [1]. As the most critical research needs for distillation were identified:

- improved understanding of physical phenomena
- better in situ sampling
- analytical and flow-visualisation methods
- better predictive modeling

At the AIChE Spring Meeting in Atlanta in 2000 there was a special panel discussion on distillation. The goal of this symposium was to follow up on the Vision 2020 Distillation Roadmap and to discuss with world leading experts the future research and development requirements [2]. The panel discussion identified the following most important aspects of distillation equipment:

- No real alternative to distillation
- In 20 years distillation is still the key unit operation as today
- Some replacements are expected: more hybrid/combined processes (distillation with crystallisation, with membranes, etc). Some people believe up to 20%!
- Hardware: No big step forward is expected: The big improvements have been made in packings and trays over the last years. James Fair stated: "Most new designs and retrofits will employ devices similar to those found today."
- For structured packings:  
less fouling in packings and distributors  
Less space for liquid distribution, wider operating range
- Imaging techniques (scanning, tomography, etc): Imaging of malfunctioning columns will become a powerful diagnostic tool. One expects a big step forward in this area.

This paper is an update of our Atlanta contribution and last year's paper at the GVC meeting in Bamberg. It is an attempt to fundamentally better describe the performance of structured packings and to derive the possible improvements for distillation columns in the next decade.

## **DEVELOPMENT OF STRUCTURED PACKINGS**

Since the 1960's structured packings have been applied successfully in industrial distillation and absorption columns. The early packings were BX gauze packings. They were used for the separation of heat sensitive products. In the 1970's Mellapak structured packings opened up a large field of applications in chemistry, petroleum chemistry, refinery and absorption processes. For a long time it seemed as if the optimum was already reached with this geometry of corrugated sheets and its open, mutually crossing channels. In addition no better performance was achieved with various packings of similar geometry (Figure 1).

An important milestone in the history of structured packings was the development of a totally new geometry in 1994: Optiflow. Because of the unique flow paths for the liquid and the gas phases the capacity was increased by 25% without any losses in separation efficiency [3].

With extensive CFD simulations and experimental tests with dozens of prototype packings of different geometry in our laboratories we finally developed in 1999 an improved structure of corrugated sheet packings: MellapakPlus. This new structure is especially designed to avoid premature flooding in any region of the packing. Compared to conventional Mellapak the pressure drop is remarkably lowered, and the maximum useful capacity could be extended up to 50 % [4].

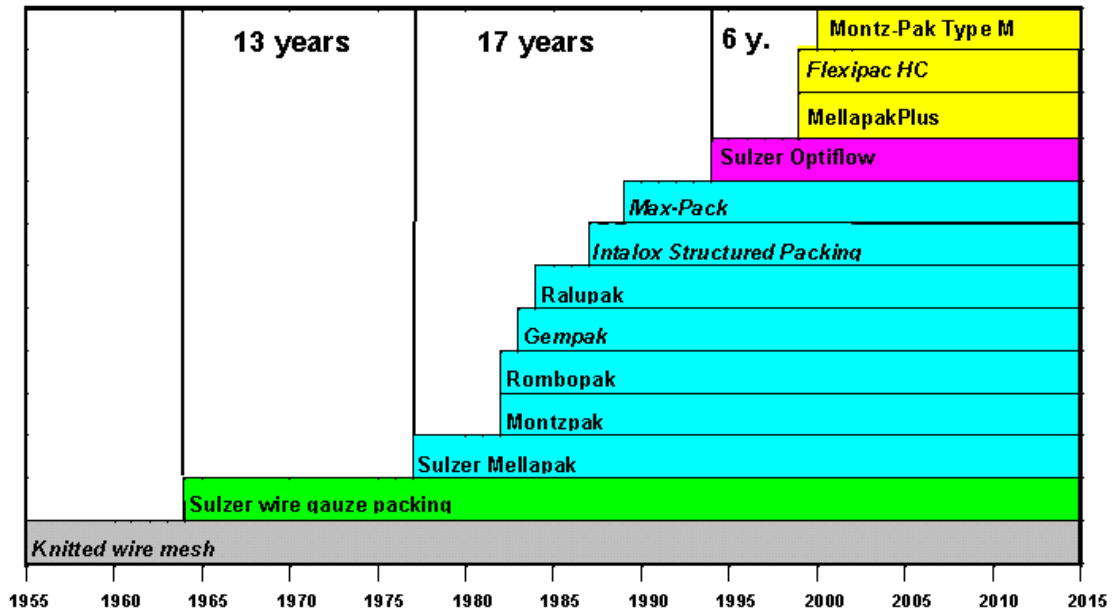


Figure 1 History of structured packings

What may be learned from the history? The time between major developments seems to decrease: from average 15 years until the 80ies down to 6 years since the 90ies. This observation leads to the assumption of the following trend:

### Trend 1

Acceleration of innovation cycle with the following goals

- increase separation power per unit volume
- decrease equipment cost
- understand the physics of the mass transfer process

## COMPARISON OF PERFORMANCE

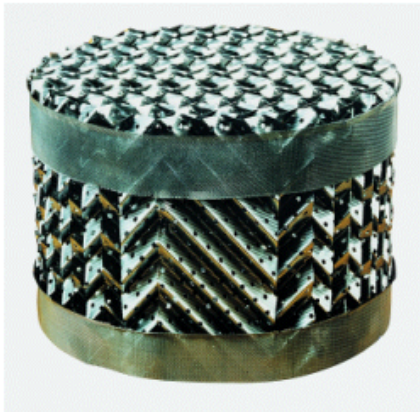
### Performance Diagrams

The purpose of the following is to develop a method to estimate possible improvements in performance (capacity, efficiency, pressure drop).

Mellapak, MellapakPlus and Optiflow were chosen as typical representatives of different packing structures (Figure 2). The traditional way to present the performance of packings is by plotting efficiency ( $NTSM=1/HETP$ ) and pressure drop versus gas load (F-factor). Our published experimental data have been taken in a 1m diameter distillation column at total reflux and different top pressures. Standard test mixtures are chlorobenzene/ethylbenzene or trans-/cis-decaline. Performance data at 100 mbar top pressure of the three packing types are plotted in Figure 3.

Why has the operating pressure of 100 mbar been selected? Structured packings have their main application in vacuum distillation, therefore 100 mbar is a typical operating pressure, e.g. in the separation of ethylbenzene/styrene.

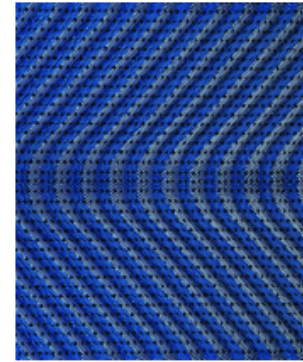
Despite the fact that holdup data are important for the understanding of the dynamic behaviour of the columns only little information is available from vendors [12].



Mellapak



Optiflow



MellapakPlus

Figure 2 Different packing structures

A direct comparison of the performance of different packings based on these standard charts is difficult because of

- different test mixtures
- different test columns (diameter, packing height)
- different operating pressures
- different liquid distribution methods
- unknown VLE method

An exception is the test work of Fractionation Research Inc., which is limited to its members.

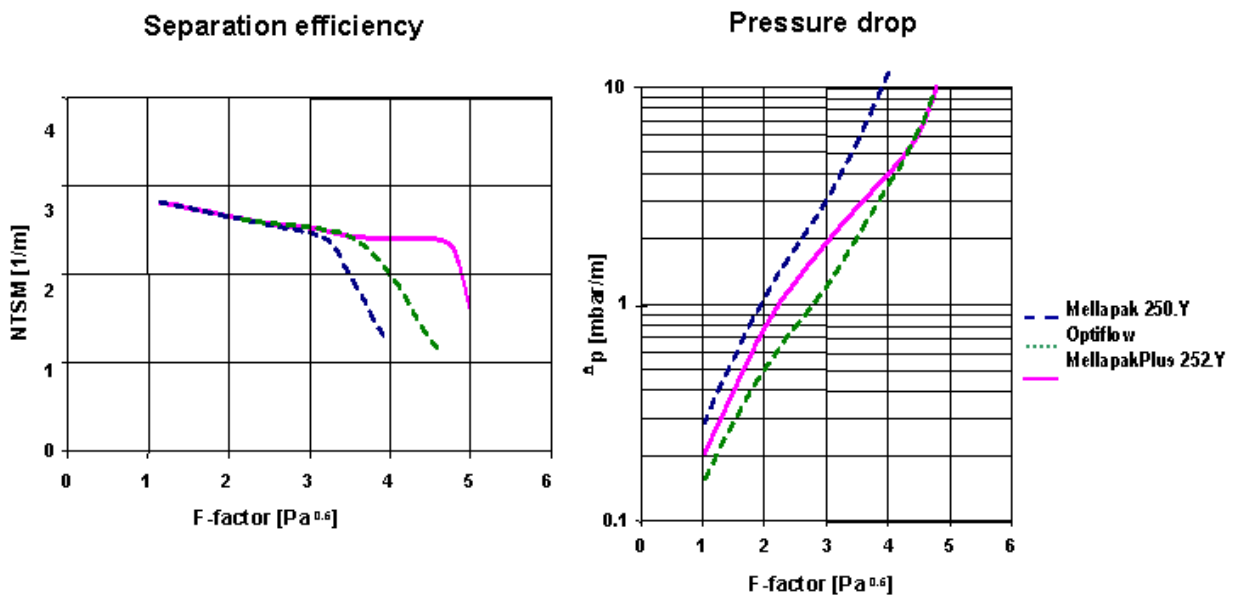


Figure 3 Standard performance diagrams

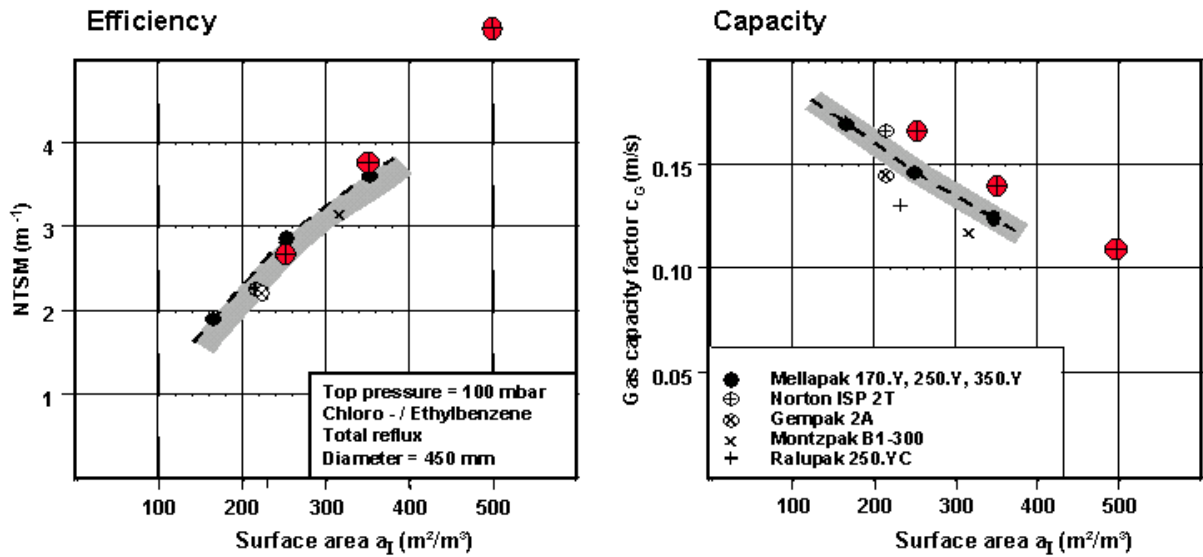


Figure 4 Efficiency (NTSM) and capacity factor ( $c_G$ ) versus geometric surface area ( $a_1$ ) for different packing types (red symbols for MellapakPlus)

In Figure 4 the efficiency and the capacity of sheet metal packings of different vendors are plotted versus the geometric surface area of the packing. We can see that the efficiency for a fixed surface area does not vary significantly and for many years no improvements have been made.

### Separation Power

A fair comparison of different packings based on such performance diagrams as shown in Figure 4 is not easy and may even result in wrong conclusions. An alternative way of comparison is to investigate the separation power of the packings. The separation power is defined as the product of gas load (expressed by the Ffactor  $F_v$ ) times efficiency NTSM ( $=1/\text{HETP}$ ). It is a measure for the packing volume used for a given separation task. The higher the separation power, the lower the volume needed.

For most of the common structured packings the separation power is very similar. In the last few years a considerable step forward has been made with the structured packing Optiflow and very recently with high capacity packings, e.g. MellapakPlus.

In Figure 5 we try to combine the separation power with pressure drop properties. The pressure drop is important for difficult separations in the vacuum where it is very often the decisive factor. In this figure we clearly see the significantly different behaviour of the three packing types, the traditional Mellapak and the recently improved types Optiflow and MellapakPlus. Optiflow (with a surface area of  $210 \text{ m}^2/\text{m}^3$ ) shows a high separation power per surface area at a low pressure drop. MellapakPlus (with  $250 \text{ m}^2/\text{m}^3$ ) peaks at a 10% higher separation power, but at a three times higher pressure drop. The separation power has been increased by 50% for MellapakPlus compared to Mellapak.

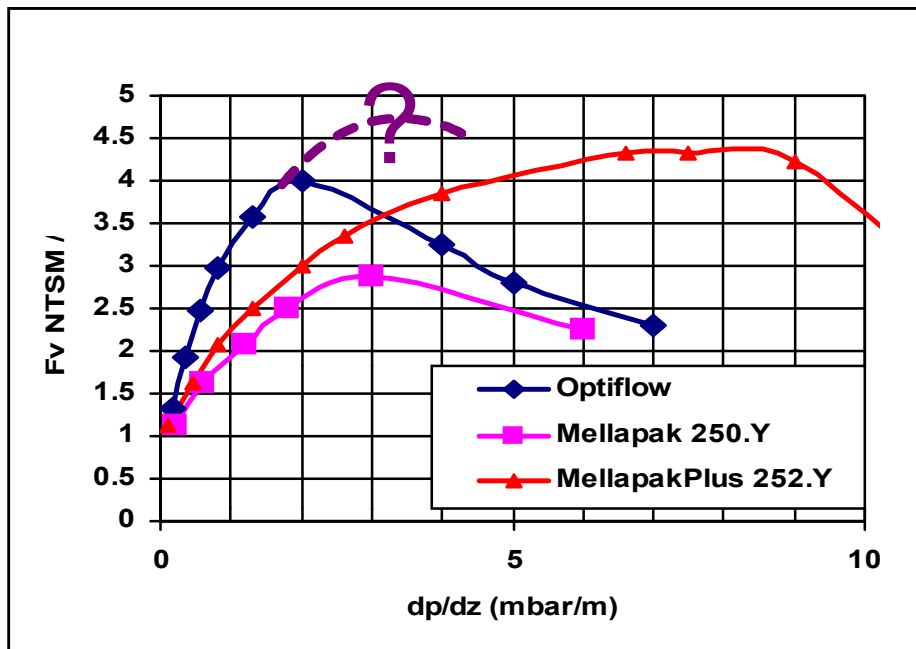


Figure 5 Separation power per  $100 \text{ m}^2/\text{m}^3$  of surface area versus pressure drop. The dashed line with the question mark indicates our vision for this decade.

## Trend 2

Our vision is to develop a packing with an even higher separation power at an intermediate pressure drop. We assume that a combination of the two structures will lead to a further increase in separation power during the next innovation cycle. The optimisation of the gas and liquid flows in the future packing geometry will be of major importance. A further cost reduction based on optimised manufacturing methods will be also a main topic.

## High Liquid Load / High Pressure Services

The use of structured packings in high liquid load / high pressure services is often questionable and not clear in industrial practice.

Most of the confusion arises from the fact that many engineers do not distinguish between high pressure applications in distillation, with a low ratio of liquid to gas density ( $\rho_L / \rho_G < 20$ ) and applications in absorption or stripping processes with a high ratio of liquid to gas density ( $\rho_L / \rho_G \gg 20$ ). In the latter case, the design and behaviour of structured packings is well known and state of the art. A safe design can be made. Typical absorption examples are e.g. glycol contactors, where numerous columns are operated with pressures of up to 150 bar. Examples for high liquid loads are e.g. sea water deaerators with liquid loads of up to  $300 \text{ m}^3/\text{m}^2\text{h}$ .

The situation is different in high pressure distillation applications [13]. The vapour / liquid interaction at  $\rho_L / \rho_G < 20$  and low surface tensions ( $\sigma < 0.005 \text{ N/m}$ ) is still not well-understood. Even the thorough study by Baenziger [10] could not bring light into the dark. Due to the poor understanding of the phenomenon it is recommended to be very cautious applying structured packings in high pressure distillation above 10 bar.

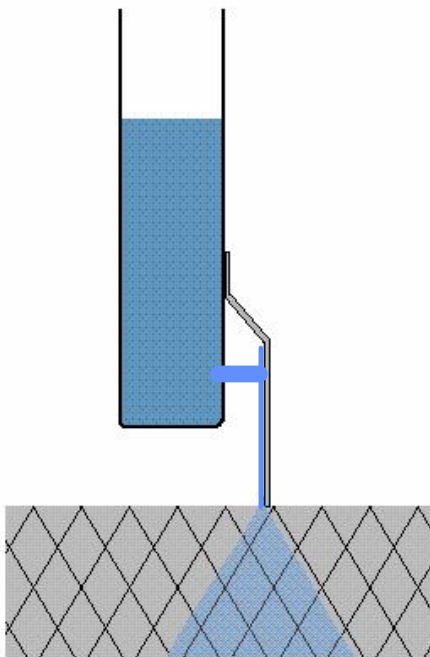
For high pressure distillation services, we need more information about the vapour / liquid interaction of structured packings in order to understand the reduced efficiency at low vapour to liquid density ratio and at low surface tension. We believe that further investigations using modern design tools, such as CFD, which are currently being developed, will help to overcome the problems .

## LIQUID DISTRIBUTORS

The design and manufacturing of high quality liquid distributors providing an uniform liquid distribution is known and state of the art. Problems still arise with the outlet holes plugging. An improvement has been made with splash plate devices resulting in a considerable reduction of hole number and a larger hole size. The plugging could be substantially reduced. A further improvement was achieved by changing the form of the splash plate into a more streamlined form (Figure 6). This resulted in a higher possible gas flow rate of up to a maximum F-factor of  $4.5 \text{ Pa}^{0.5}$  and a liquid flow rate of a maximum of  $50 \text{ m}^3/\text{m}^2\text{h}$ .

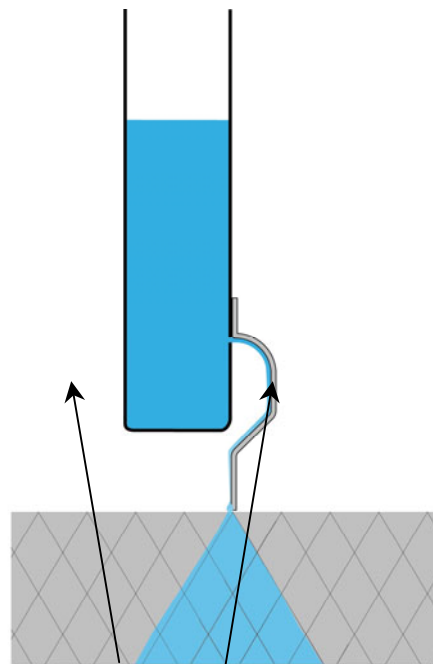
### Original design

F-factor  $< 3.3 \text{ Pa}^{0.5}$ , liquid load  $< 25 \text{ m}^3/\text{m}^2\text{h}$



### Advanced design

F-factor  $< 4.5 \text{ Pa}^{0.5}$ , liquid load  $< 50 \text{ m}^3/\text{m}^2\text{h}$



*Figure 6 Splash plate distributor development*

An other example is the tubed drip channel distributor with modified outlet tubes (Figure 7). The new developed drip tube in the form of a curl allows a much higher liquid throughput and an optimised liquid flow inside the trough. The low interaction

with the gas phase is comparable with the original design and the new design tolerates high vapour velocities (up to F-factor of  $5 \text{ Pa}^{0.5}$ ).

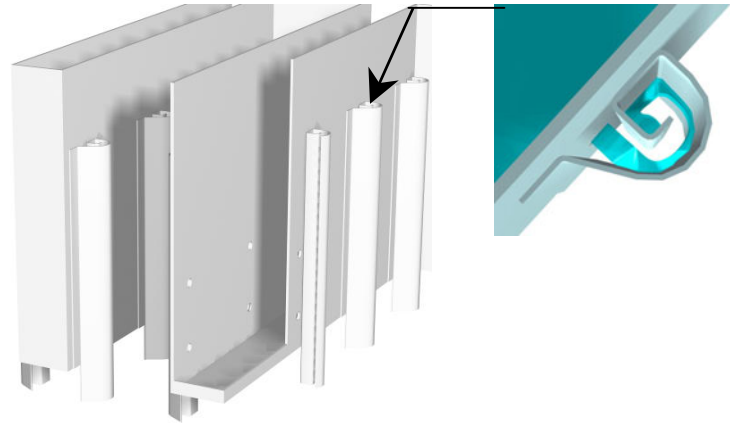
**Original design**

liquid load  $< 15 \text{ m}^3/\text{m}^2\text{h}$



**Advanced design**

liquid load  $< 80 \text{ m}^3/\text{m}^2\text{h}$



*Figure 7 Tubed drip channel distributor development*

Another problem is the height needed for redistribution. Can it be further reduced? A substantial height is used to completely remix the liquid. We do not know to which extent a complete remixing is necessary. A substantial reduction of liquid mixing could reduce the redistributor height considerably [14].

**Trend 3**

Distributors will develop to more streamlined forms to increase capacity and to reduce plugging. Redistributor height may be reduced, especially in case of column revamps, if less remixing can be tolerated. The main task in the next decade will be the investigation of the degree of mixing needed.

Due to advances in manufacturing methods a major cost reduction can be expected as well.

**COMPUTATIONAL FLUID DYNAMICS (CFD)**

CFD has become more and more important for the development of packings, internals and design of column accessories like gas entries. A recent overview of CFD-applications for the process industries is given in [6-7].

In the following the state of the art for gas and liquid phase flow is discussed separately.

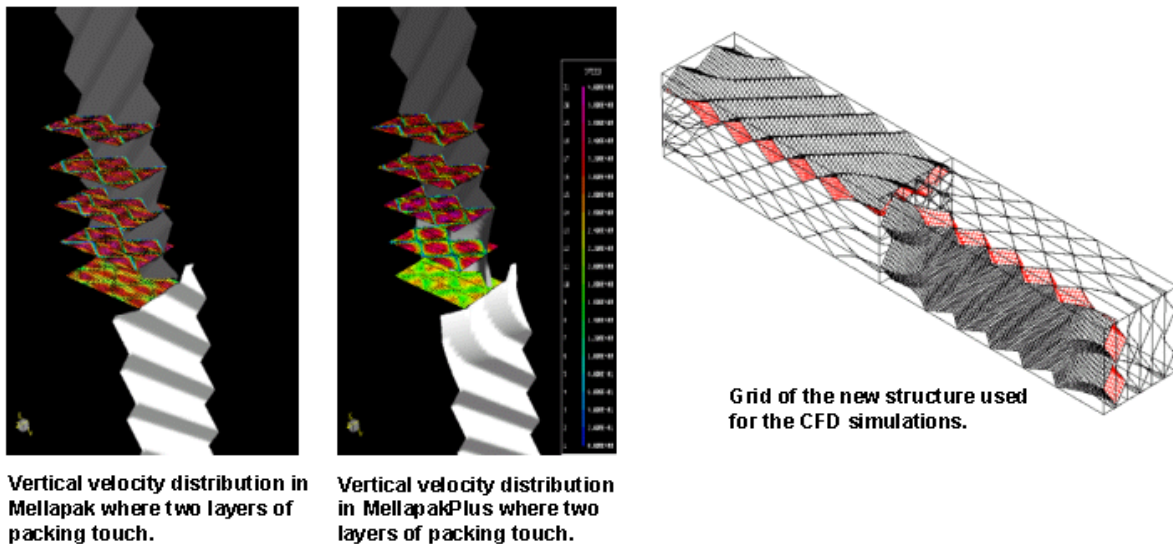
**Gas Phase Flow**

The state of the art is the simulation of the gas flow in a small packing volume (with a few channels defining the main geometric structure) with periodic boundary conditions. This allows to predict the dry pressure drop and the efficiency based on the real flow profiles within the structure, avoiding the assumption of plug flow.



The development within the last 5 years has shown great progress in the methods of grid generation (time reduction of 50 to 80%) and in the resolution of the grid due to the tremendous increase in processor power. This allowed to study the transition from one packing element to the other, which was very important for the development of MellapakPlus (Figure 8).

*Figure 8 CFD simulation of Mellapak and MellapakPlus*



It is still difficult to model the influence of the surface fine structure or surface roughness. The prediction of the dry pressure drop is within 20% of the measured values. This allows to study the differences between various packing geometries on the pressure drop and the efficiency.

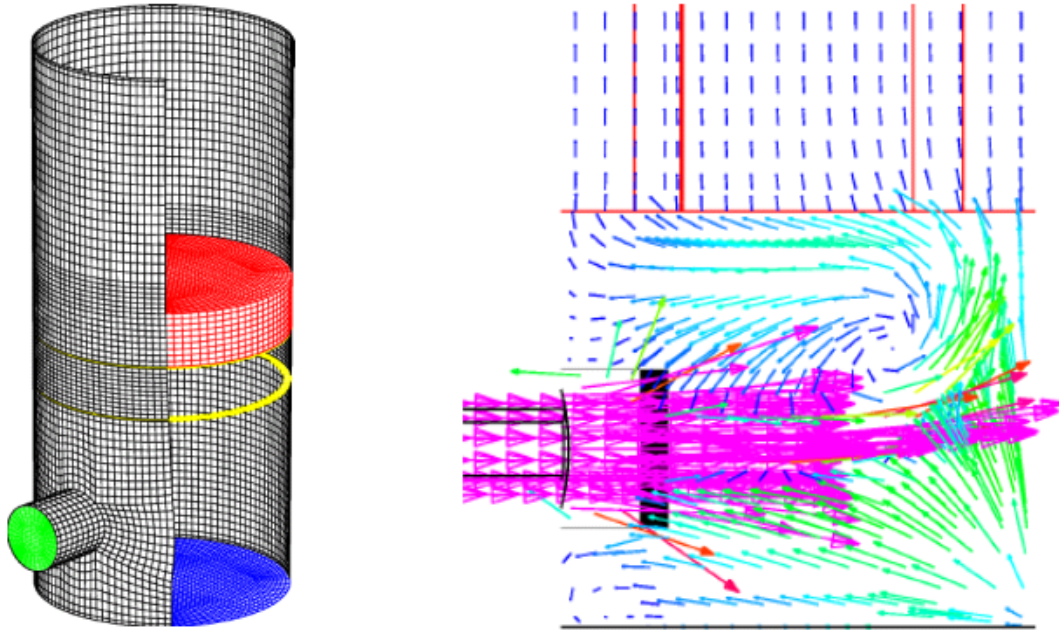
On the large scale we developed the tools to simulate the gas flow in packings, inlet devices and complete columns [11], [15]. Especially the simulation of gas entries combined with efficient grid generation allows to investigate routinely the influence of large scale maldistribution and as a consequence the packing performance. An example of the three dimensional gas flow from gas inlet to the packing is shown in Figure 9.

#### **Trend 4**

In future we will have

- more sophisticated grid generation directly from a CAD column model
- simulation of gas flow in an extended packing structure to predict its basic properties including the influence of wall effects, segmentation gaps etc.

## Gas inlet flows



*Figure 9 Simulation of the development of gas flow around the gas inlet*

### **Liquid Phase Flow**

The state of the art is the simulation of the liquid flow on an inclined plate with fine structure (objects of defined geometry on the plate). Different approaches have their own limits regarding e.g. the transition between elements or the formation and motion of drops.

An example of the flow of liquid on an inclined surface with fine structure is given in Figure 10.

### **Trend 5**

We visualise having a simulation of the liquid flow in a complete three dimensional packing structure combined with mass transfer.

Rivulets flowing down  
an inclined plane  
structured with cones of  
varying height

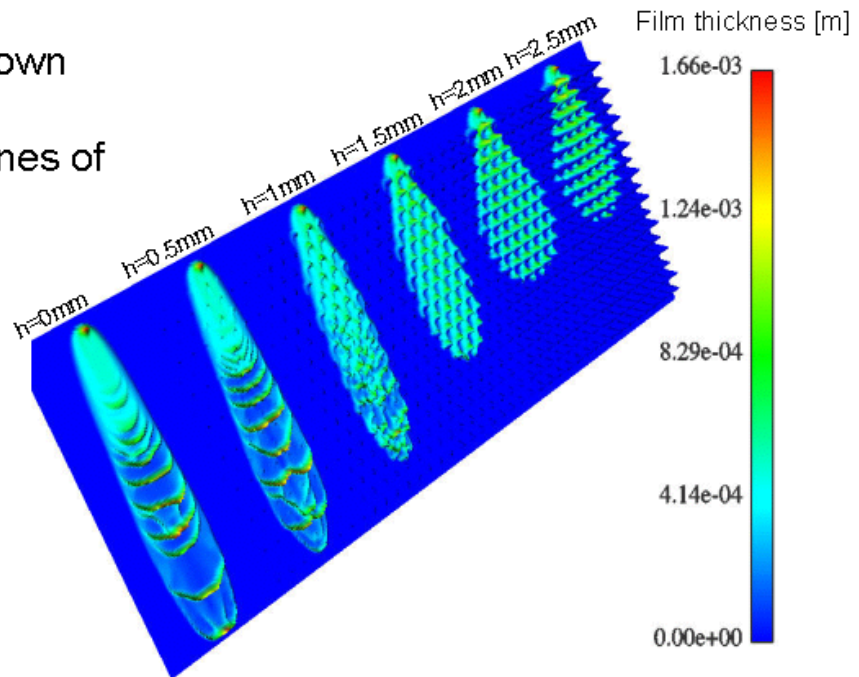


Figure 10 CFD-simulation of liquid phase flow

### Two-phase Flow

The simulation of two-phase flow is still in an early stage. The problem is that two-phase flow is an intrinsic instationary process. Today, we can simulate a two dimensional flow system where the liquid is a film on an inclined plate and the gas flow is counter-current. Much progress has been made using the Euler/Euler approach to model the liquid flow distribution influenced by gas. The difficulty here is to develop a correct description of the interaction between the two phases. An European research project is currently investigating the application of CFD for custom design of internals for heterogeneous reactive distillation packings. For details refer to the project's web page at "[www.cpi.umist.ac.uk/INTINT/](http://www.cpi.umist.ac.uk/INTINT/)".

### Trend 6

We expect that within the next 5 - 10 years real two-phase flow behaviour in structured packing can be simulated.

Simulation of the conditions in high pressure distillation or other services with mixed flow regimes will only be available later on.

It is a general trend to apply CFD more and more in research and development. It will also become important as an interface to Computer Aided Design (CAD) and Computer Aided Engineering (CAE).

## DIAGNOSTIC TOOLS (IMAGING)

Liquid maldistribution (large scale and small scale maldistribution) in packed columns is probably one of the most described effects influencing the efficiency of packed columns (see e.g. [5]). Therefore great effort, especially at the universities in Europe, is put into developing imaging tools, i.e. methods to visualise the complicated processes within a packing, column etc. In the following we present a short but not complete overview on the published work.

### Process Diagnostics

Process diagnostics is available as a commercial service for column trouble-shooting [18]. This comprises:

- Gamma- or X-ray-Scanning
- Radioactive tracing (source brought into equipment)
- Neutron moderation

Recently, hybrid services were developed:

- Spect scan: gamma scanning and radioactive tracing combined
- CAT scan (variable chord length and angular orientation)
- Tracerco Profiler: permanently installed density/level detection device (e.g. in oil water separators)

### Tomographic Techniques

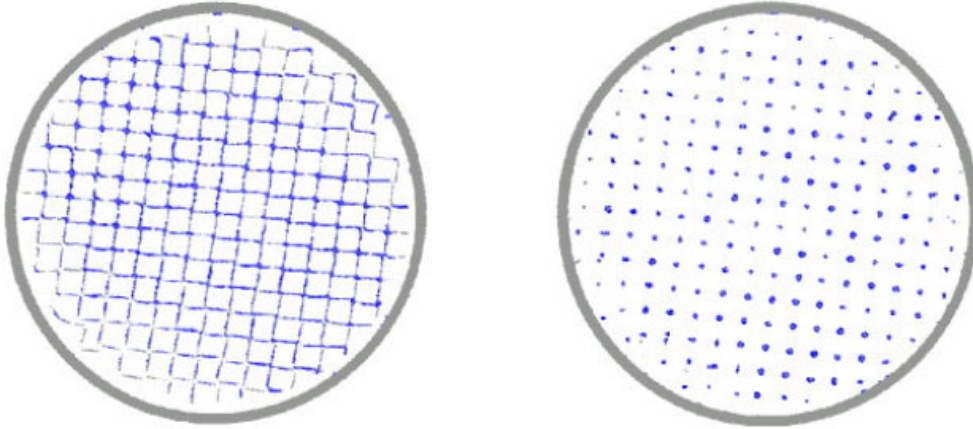
Different methods are available to determine the distribution of the liquid phase in the packing structure.

Mewes at the University of Hannover measured the liquid holdup distribution of Optiflow in a 190 mm column using X-ray tomography. A problem is how to translate liquid holdup information into a velocity distribution. If a liquid film is assumed, its velocity is derived from the film thickness using a Nusselt film type model. Details of the method and some results may be found in [8]. Figure 11 shows examples of the reconstruction of the liquid distribution in two horizontal planes in Optiflow.

Problems of this technique are insufficient spatial and temporal resolution, occurrence of artefacts [17].

Stichlmair and co-workers at the Technical University of Munich investigated the temperature distribution in Sulzer gauze packing and other types of packing to visualise the velocity profile [9].

All these university efforts help to better understand the fluid phase behaviour and to develop physically based models (see also [16]).



*Figure 11 Computer tomogram of Optiflow  
liquid load: 26 m<sup>3</sup>/m<sup>2</sup> h of water  
column diameter : 190 mm, atmospheric pressure*

### **Trend 7**

Certainly imaging will become more and more important in research and development to support better understanding of the complicated two-phase flow within packing structures. In the short term improved spatial/temporal resolution of the devices may be expected.

Imaging complements CFD, especially for validation purposes.

We can imagine to use tomogram techniques routinely like a gas chromatograph or a flow meter in the next decade's process equipment.

## **MULTIFUNCTIONAL PACKINGS**

Are there any other solutions besides hardware development to optimise distillation processes, e.g. reduction of energy consumption? Excellent examples amongst others are reactive distillation and dividing wall columns. Both have been known for 50 years or more but have only become popular in the last years.

### **Reactive Distillation**

Great progress has been made in the last few years in investigating the combined processes of catalytic reaction and simultaneous fractionation of the reaction products in a single distillation column using solid catalysts. Examples of industrial use are etherifications, esterifications (e. g. to manufacture MTBE, a gasoline additive), alkylation or hydrogenation. The advantages are obvious: Since reaction products are removed continuously from the reaction mixture, chemical equilibrium cannot be established, and high reaction rates are achieved. The results are higher conversions compared to conventional processes. A typical example is the esterification of ethyl acetate where an energy saving of up to 50% can be achieved (Figure 12). In addition, since reaction and distillation are performed in the same combined column, it can replace a separate fixed bed reactor and a separate distillation column thereby eliminating equipment and reducing capital costs.

Despite the remarkable R&D efforts at universities and in industry, the number of industrial applications of heterogeneous catalytic distillation is still small (about 100 worldwide). There were several reasons for this, such as lack of experience, simulation capability, test equipment, qualified hardware, scale up know-how, etc.

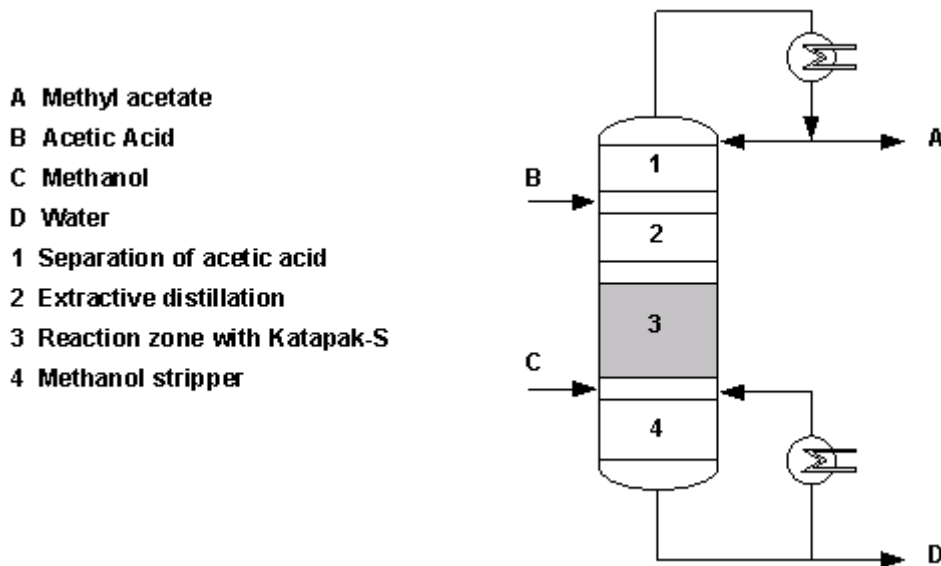


Figure 12 Reactive distillation with Katapak

### Trend 8

Today most of the above mentioned problems have been solved and a breakthrough in the next few years can be expected. The vision is to increase the number of columns from 100 to 1000 during the next decade.

### Dividing Wall Columns

The fully thermally coupled column system and the dividing wall column (Figure 13) are both thermodynamically equivalent, and have been known for 50 years. But in practice they have not found a widespread industrial use, although in the last 10 years the number of applications has increased. There are several reasons for this, e.g. more difficult to control, less flexibility, difficult to distribute vapour and liquid flow, etc. Several investigations have shown the big potential to reduce the vapour flow and therefore the energy consumption compared to conventional distillation systems. Besides the lower energy consumption the dividing wall column is attractive because the system requires only two heat exchangers (for a three component system) and a smaller overall column.

### Trend 9

Today, the dividing wall column system is accepted mainly in chemical and petrochemical applications and a significant increase in use of this system may be expected in the next 10 years.

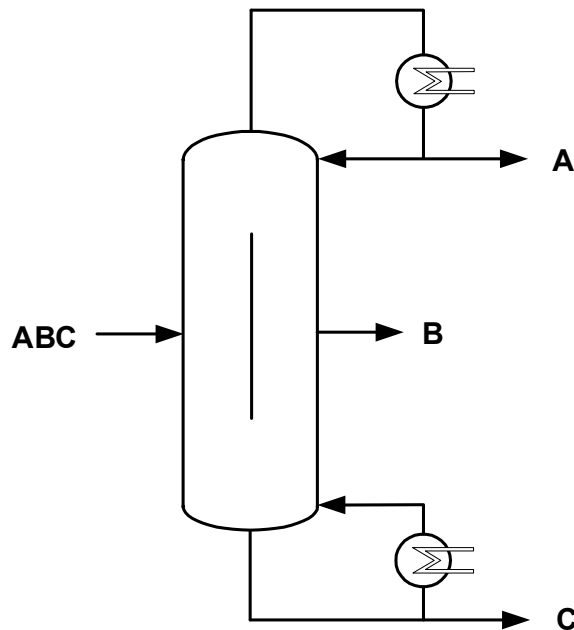


Figure 13 Sketch of dividing wall column

## OUTLOOK

We see two different developments, the first focuses on equipment, the second on tools.

Regarding equipment we expect:

- Shorter innovation cycle
- Increased separation power of structured packings at an intermediate pressure drop
- Cost reduction
- Streamlined, cheaper internals

Many questions remain unanswered: Where is the physical limit? How much can safety factors be reduced? etc.

Regarding tools

- CFD and imaging will become more and more important in R&D
- Long term goal is the virtual packing (i.e. real two-phase flow simulation in a packing structure)
- Imaging complements CFD (Validation)

We do not expect a too rapid change in the process industries because of its very conservative attitude. By the need to remain competitive all options to reduce energy consumption, investment costs, waste, etc. have to be considered and decisions have to be taken. We believe that by the end of this decade distillation will still be the

main separation process within its limits but other options like e.g. combined unit operations would have to be considered and evaluated.

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