CHARACTERISATION OF HIGH PERFORMANCE STRUCTURED PACKING

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ABSTRACT

Column packings applicable to the field of rectification are mainly characterised by their number of theoretical stages per meter NTSM [1/m], specific pressure drop Δp [mbar/m] and capacity limits. A set of dimensionless numbers are derived by means of a simple model of dry gas flow within parallel plates (slit flow). These numbers are dimensionless and allow the comparison of measured values from various packing types and their recently improved performance whilst only taking into account the specific surface. These numbers describe pressure drop, capacity and surface efficiency.

Furthermore, a different heuristic approach is presented where the most important criteria describing packing performance are combined into one characteristic number which is plotted against a capacity factor. Characterisation of packings can thereby be concentrated within one single diagram.

Examples of values from different packing types are presented. The recent developments of new generations of high performance packings are included. The investigations undertaken allow extrapolation and therefore performance prediction of further developments.

STRUCTURED PACKING IN DISTILLATION APPLICATIONS

Structured packings have been established in the field of distillation for several decades. They are preferred where a high separation performance is required and low pressure drop is of importance. A column design with several beds, liquid collectors and distributors is challenging and requires the consideration of many details. Driven by various needs for different applications during the recent decades several types of packing have been developed and are successfully used throughout process industry. They might be distinguished as follows:

Gauze packing
Grid type packing
Corrugated sheet packing
Random packing

For each application, the different packing types have several advantages. For instance, random packing is generally the best choice for applications with very high liquid loads, whereas, gauze packing tends to be the best choice for operation at very low pressures and liquid loads. Metal sheet and grid type packings are suitable for a wide range of applications and are particularly suited to applications where the maximum allowable pressure drop and limitation in height, combined with a high separation requirement, are of importance.

In addition to the degree of flexibility in terms of column height and diameter, the designer is confronted with different potential suppliers and their different packing types (leading to different column dimensions).

Our contribution has the intention of presenting measurable criteria allowing a neutral and fair comparison of different types. They are best explained with the help of examples and for this reason we have chosen some "typical" and in the market well known packing types, although we know that this selection is not complete.

Parameters

Column packings applicable to the field of rectification are mainly characterised by their number of theoretical stages per meter NTSM [1/m], specific pressure drop Δp [mbar/m] and capacity limits.

The packing performance is mainly influenced by:

vapour mass flow rate	$\dot{G}$	[kg/h]
gas density	ρ_g	[kg/m³]
f-factor	f	$\sqrt{Pa}$
liquid mass flow rate	$\dot{L}$	[kg/h]
liquid density	ρ_l	[kg/m³]
liquid load	v_l	[m³/m² h]
viscosities	$\eta_g, \eta_l,$	[Pa s]
surface tension (g-l)	σ	[N/m]

The packing might further be characterised by the description of its structure [1] like void fraction, grid angles, hydraulic diameter of channels (if present), and typically very often simply by its specific surface area a [m²/m³].

Reference geometry

As a model geometry of reference we have chosen the infinite parallel plates (slit flow) with the same specific area *a* as the packing in consideration.
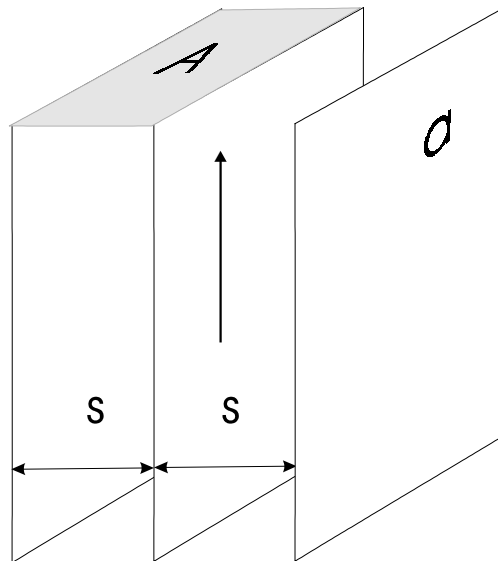

Figure 1: Reference geometry parallel plates

This reference geometry needs only to be characterised by the distance of the plates to each other; their spacing *s*. Deriving the hydraulic diameter d_h for any arbitrary packing and for the infinite plates we apply the known ratio of cross section *A* to circumference *U*.

$$d_h = \frac{4 \cdot A}{U} \qquad (1)$$

resulting into

$$d_h = 2 \cdot s = \frac{4}{a} \qquad (2)$$

This hydraulic diameter might differ to that derived according to the specific geometry of certain packings (e.g. channel diameter for a corrugated sheet). The advantage of this definition is its universal applicability for any arbitrary geometry of a structured or random packing.

Rombopak structure

In the following sections data from different packing types will be presented (Mellapak, Rombopak, VSP, Nutter Ring, Pallring). Rombopak is the packing of Kühni [4], hence the focus of our development work is its further improvement. Due to this we are able to present recently measured data that can be compared with other packing type's data. As not all readers might be familiar with the grid type packing Rombopak, it is depicted below.
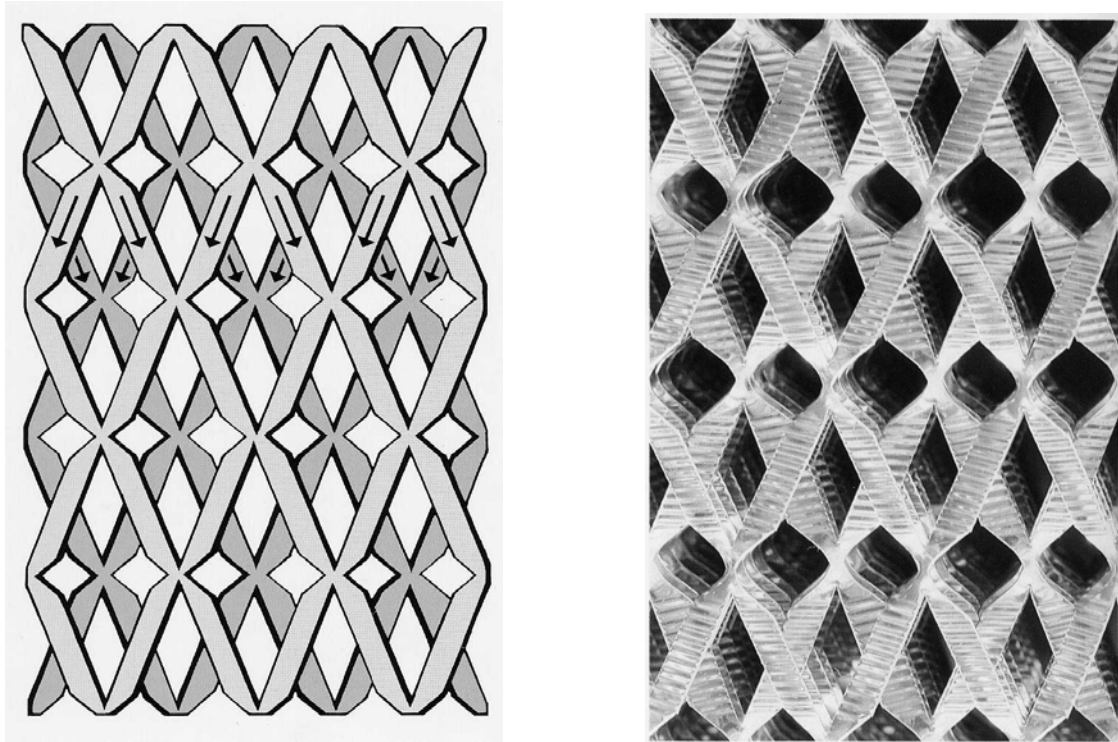
Figure 2: Rombopak structure

Unlike other systematic column packings its surface is divided into a multitude of small lamellas.

CHARACTERISTIC NUMBERS

In designing a distillation column the engineer has typically establshed the process and is then confronted with the duty to choose the best column design. This is an interesting task and the engineer has the advantage (problem) of internals selection and the evaluation of their impact on column design and process (-costs).

The well known, but still challenging objective, is to find the packing which provides a high NTSM [1/m], and produces the lowest possible pressure drop Δp [mbar/m]. For new installations, the optimal packing leads to the smallest (most economic) column, whereas, for retrofits the highest possible capacity (besides improvement of Δp and NTSM) is often of importance. Hence we detect a demand for objective and ideally simple criteria for packing comparison.

Pressure drop, N_p [-]

Pressure drop becomes important at low absolute operating pressures. The demand for processes at very low operating pressures is increasing significantly. For instance, the development of new pharmaceutical products (active ingredients) results in more and more complicated molecules. These are generally temperature sensitive and can only withstand moderate temperatures. Another example is processes where natural ingredients are extracted by means of solvents which then need to be distilled off under very low pressure conditions. Due to the current trend of custom manufacturing in the fine chemicals industry nowadays more engineers are faced with such problems than before.

Δp for a given structure (here Rombopak)

The specific pressure drop depends on structure type and specific surface area. In order to investigate its theoretical limit (to check the horizon) we compare measured values with calculated ones from parallel plates with identical specific surface.

In the following diagram we have depicted measured and CFD calculated values of pressure drop versus f-factor for the structure Rombopak 4M. These are compared with the calculated values for the infinite parallel plates.
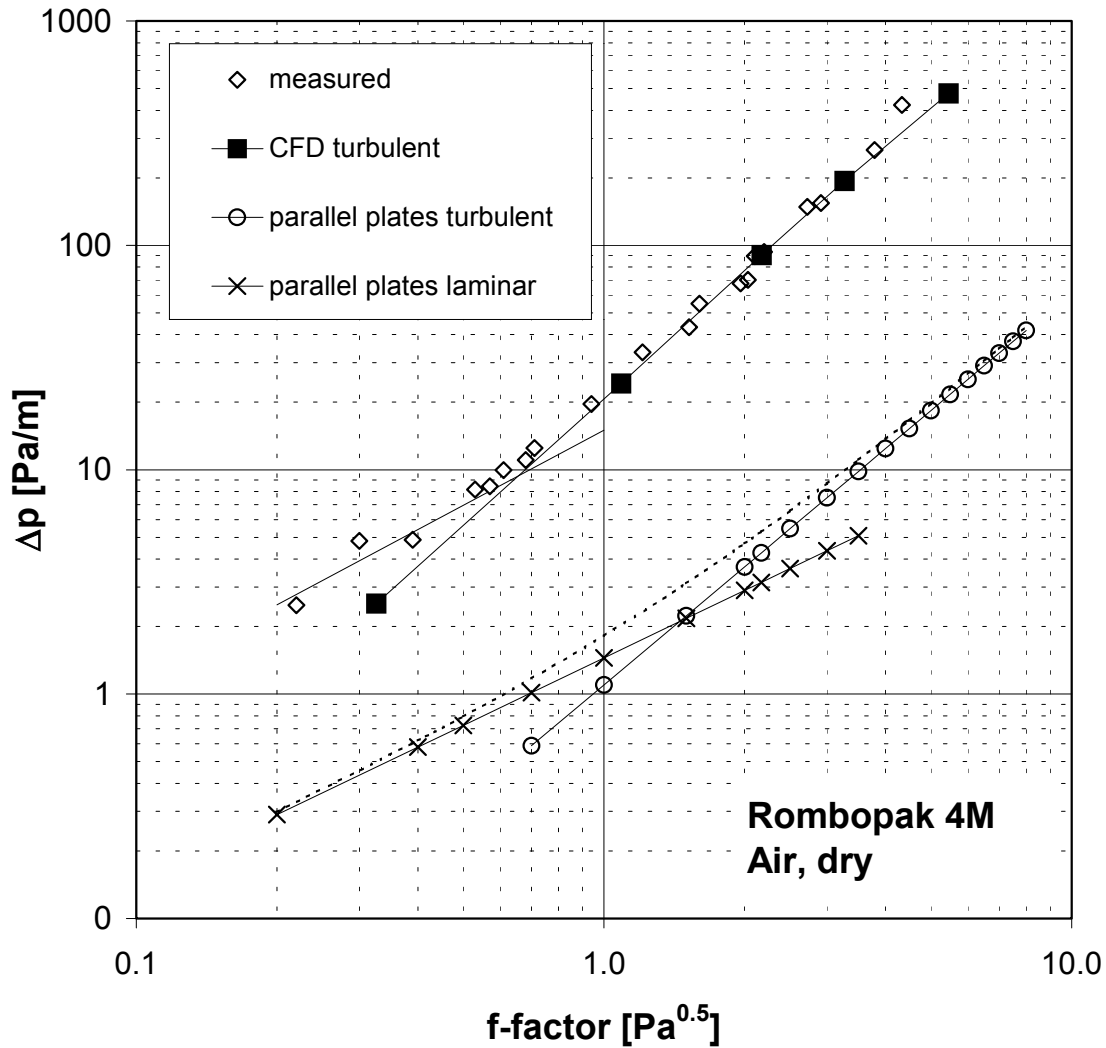

Figure 3: Measured pressure drop for Rombopak 4M in comparison to calculated pressure drop by CFD [2] and calculated pressure drop for slit flow with identical specific surface a (eq. 3-5).

The diagram shows that the principle slope of the curve can be described by calculating pressure drop analytically for the infinite plates with the same specific surface *a* according to:

$$\text{Re} = \frac{f \cdot 4}{v \cdot \sqrt{\rho \cdot a}} \tag{3}$$

$$\Delta p = \zeta \cdot \frac{f^2 \cdot a}{8} \tag{4}$$

$$\Delta p = \sqrt{\Delta p_{lam}^2 + \Delta p_{turb}^2} \tag{5}$$

The "difference" between a real packing and the infinite plates can be taken as a characteristic value. We define

$$N_p = \frac{\Delta p_{packing}}{\Delta p_{slitflow}}$$ (6)

We choose a typical value of f = 1.5 and find for our example the value of $N_p \approx 14$.

Knowing about this significant difference one consequence during a recent development project from Kühni was to modify the intrinsic structure in order to design structures with features that lie closer to those of infinite plates [2].

Changing the structure with the objective of reducing pressure drop has always to be regarded in context with restrictions in separation performance (maintaining the surface wetting and structure as similar as possible to the original). The improvements reached so far have been obtained by systematically analysing the above mentioned criteria, applying modern CFD analysis, and also undertaking classical simple experiments. This has led to a new packing type **Rombopak S** with improved overall performance (fig 4) [2][4]. Regarding the results we see a clear potential for further significant reduction of pressure drop by further modifying the structure. In the following diagram measured pressure drop values for Rombopak and Rombopak S are presented and for comparison also the calculated values according to equations (3), (4) and (5) for chlorobenzene / ethylbenzene.
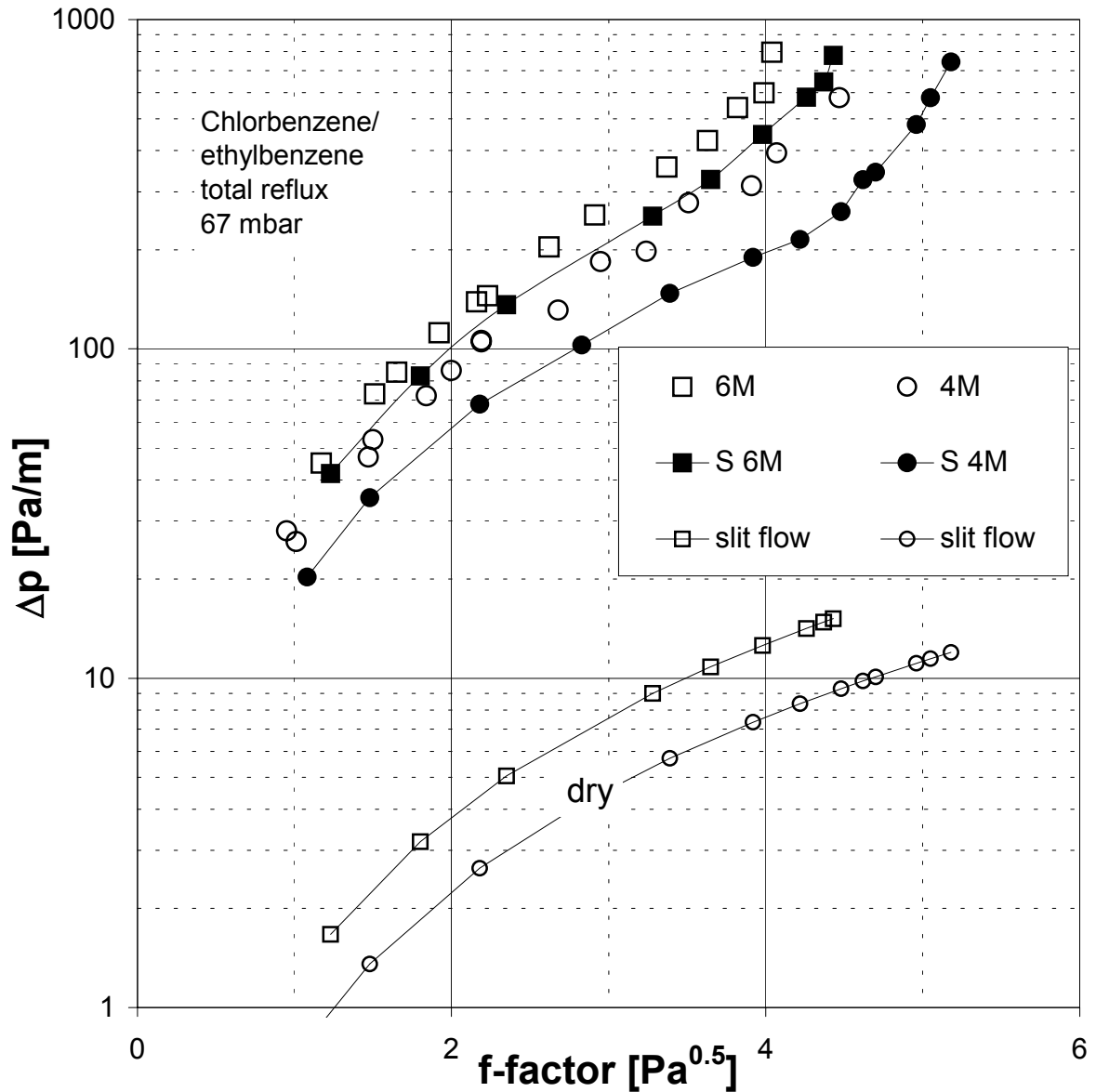
Figure 4: Measured pressure drop for Rombopak (⌀ 250 and 800 mm, bed height between 2 and 4 m [2]) in comparison to analytically calculated pressure drop for slit flow with identical specific surface.

Δp for different structures

Any structure has its specific values for N_p (that can eventually be improved further). In the following diagram values for N_p versus f for different packing types are shown. For Rombopak we took the same values as shown in fig. 4. For comparison we added values from Mellapak [Sulpak 3.0].
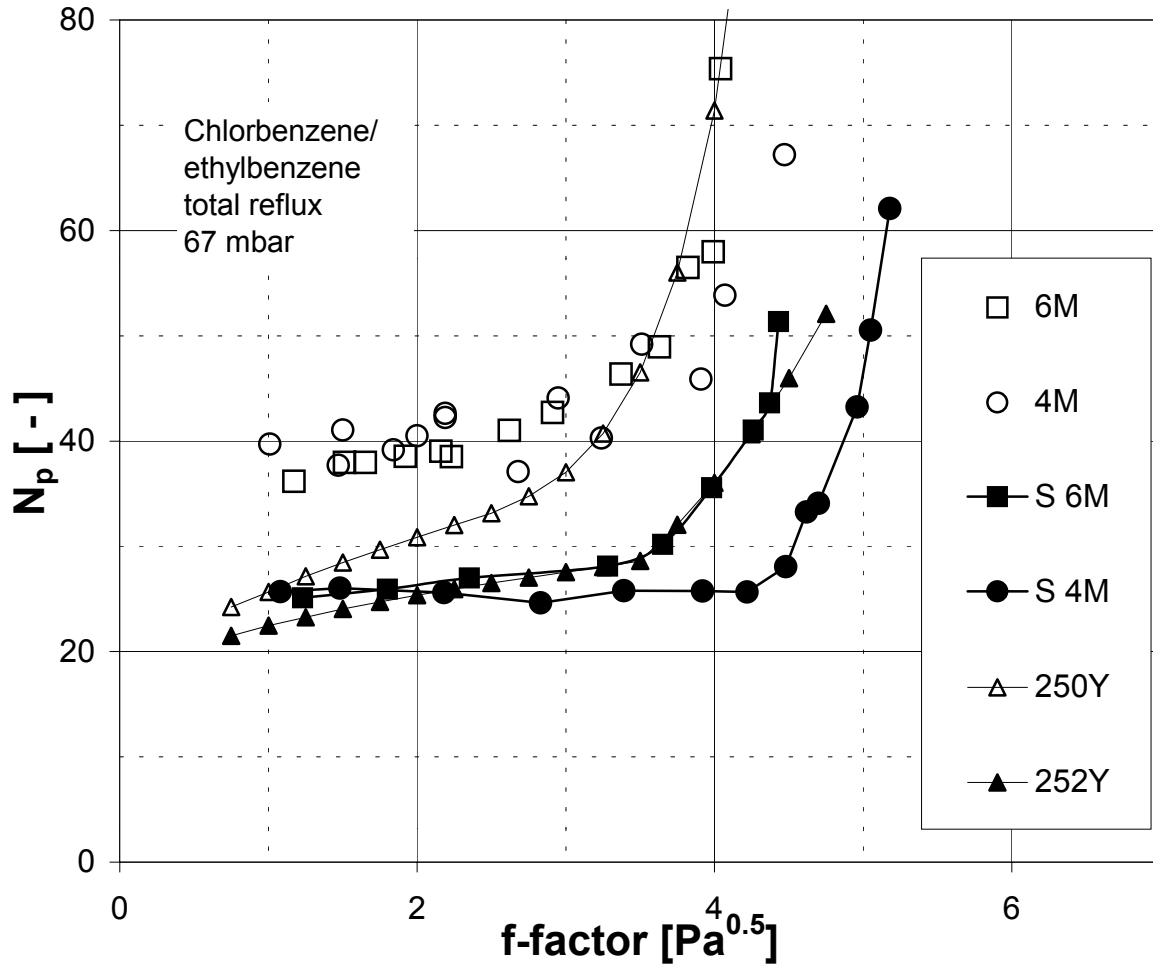
Figure 5: N_p (eq. 4) versus f for Rombopak and Mellapak.

In the region of lower f-factors we observe a "plateau" which for Rombopak lies in the region of 40, whereas for Rombopak S it lies between 20 - 30, hence the improvement in pressure drop can determined to be about 30 to 40%. The increase of Np with higher f-factors is due to the shortcoming of the model which does not include flooding behaviour.

Capacity, N_C [-]

The cross sectional area of a distillation column is chosen in accordance to the possible specific gas load expressed as f-factor.

$$f = v_g \cdot \sqrt{\rho_g} \quad [\sqrt{Pa}] \tag{7}$$

where v_g is the gas velocity in m/s.

Typically the chosen f-factor lies (with a sufficient margin) as close as possible to the maximum possible f_{max}, defined as f at "flooding point". The definition for the flooding point is practically chosen by its effect to the pressure drop: The build-up of liquid causes pressure drops of more than 12 mbar/m (definition).

Flooding points (f_{max}) are depicted usually [3] in capacity diagrams where the capacity

$$C = \frac{f_{max}}{\sqrt{\rho_l - \rho_g}} \quad [m/s] \tag{8}$$

depends on liquid and gas load characterised by

$$\psi = \frac{\dot{L}}{\dot{G}} \sqrt{\frac{\rho_g}{\rho_l}} \quad [-]$$ (9)

Again we apply our model of the infinite parallel plates. The definition of C can be derived from a simplified Bernoulli equation applied to the floating drop with diameter d_c at turbulent gas flow ($c_w = 0.5$).
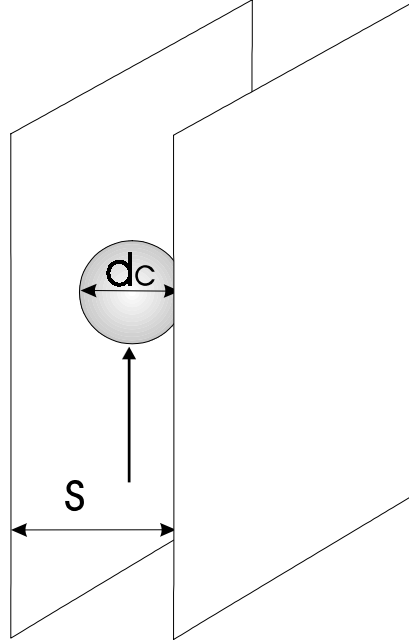

Figure 6: Floating drop within parallel plates.

A momentum balance results in

$$\left(\rho_l - \rho_g\right) \cdot g \cdot d_c \frac{4}{3} = \rho_g \frac{v_{max}^2}{2} = \frac{f_{max}^2}{2}$$ (10)

We postulate that the flooding is reached when the drop diameter reaches the slit spacing.

$$d_c = s = \frac{2}{a}$$ (11)

We are aware of not having considered several important variables like the liquid flow on the surface. However by applying this model we obtain a simple and analytical definition for the theoretical capacity limit C*. The big advantage is that a comparison of any packing type just by its specific surface is possible.

$$C^* = \frac{f_{max}^*}{\sqrt{\rho_l - \rho_g}} = \sqrt{\frac{16 \cdot g}{3 \cdot a}}$$ (12)

The * indicates slit flow. Values for C of real packings have lower values. Since we have shown that the pressure drop behaviour is similar to that one of slit flow we observe here again that measured capacity of packings follows a curve defined by the above mentioned equation. Hence we introduce a new characteristic number N_c which is a measure for capacity of different packing types:

$$C = \frac{f_{max}}{\sqrt{\rho_l - \rho_g}} = \sqrt{\frac{16 \cdot g}{3 \cdot a \cdot N_c}}$$ (13)

N_c = 1 is the theoretical limit, real packings have values with N_c > 1

fit of N$_C$
For different types of packing with similar structure but different specific surfaces *a* it should be possible to fit N_C according to measured *C*-values. This firstly allows analysis of the packing behaviour of new packing types and secondly determination of the potential for improvement in capacity for new packing types (e.g. Rombopak S) by the value of

$$\frac{C_{new}}{C_{old}} = \sqrt{\frac{N_{Cold}}{N_{Cnew}}} \tag{14}$$

The fit of N$_C$ needs to be done for a distinct (ideally small, to lie close to the chosen model) ψ-value. In the following diagram (fig. 7) values for several packing types for ψ = 0.015 are shown. The values for C are all obtained from the official vendor's brochures for the condition of ψ = 0.015 which corresponds to about 60 to 70 mbar for the test system chlorobenzene / ethylbenzene. For Rombopak these have been verified with this test system at total reflux in columns $\varnothing$ 250 and 800 mm and bed heights between 2 and 4 m [2][4].
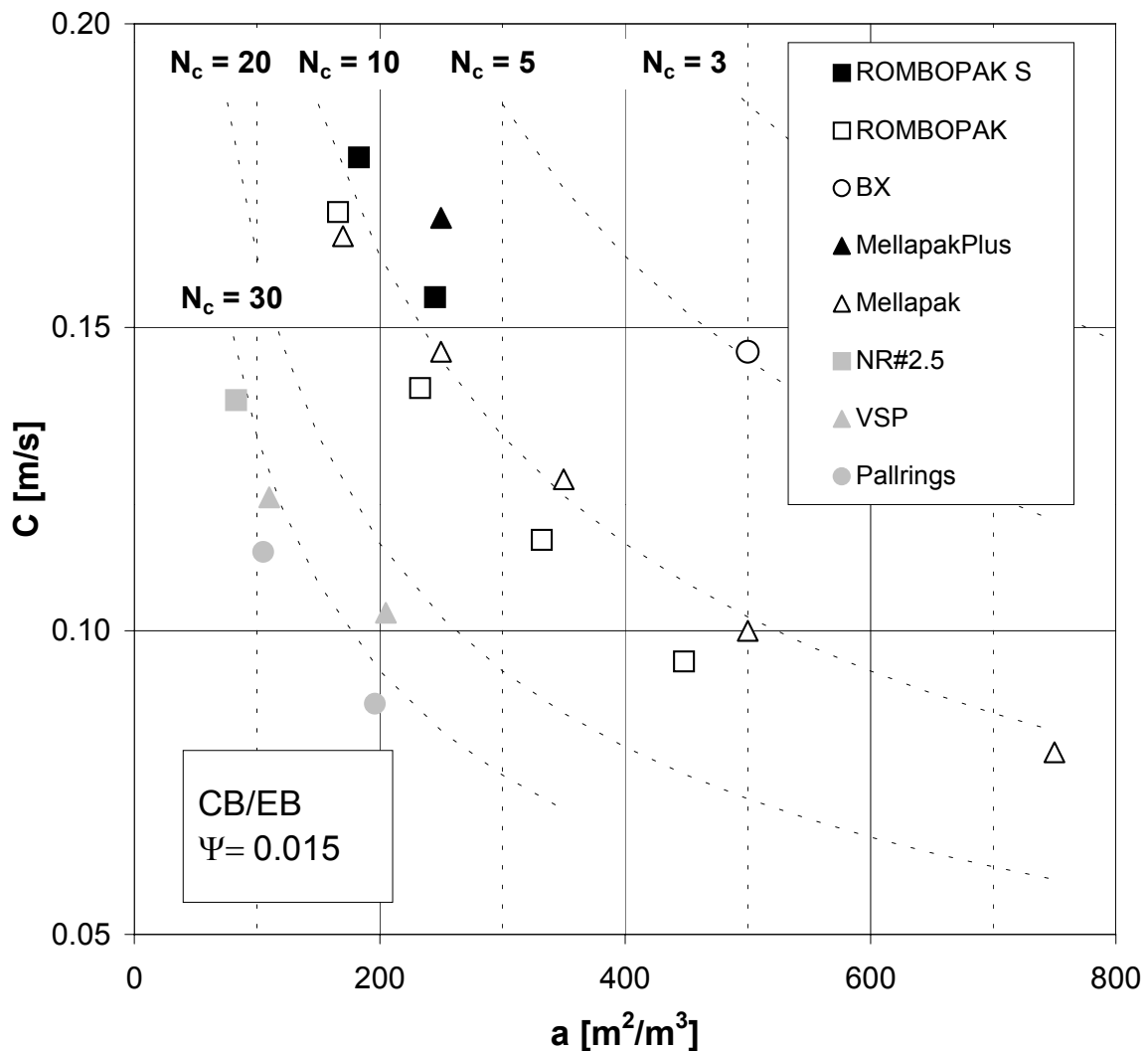

Figure 7: Capacity of different packing types. Dotted lines from equation 13.

We observe that the measured values for each group of packing type follows the curves with constant N_c. Hence this number, although quite simply derived, is able to characterise the capacity and their differences

Separation Performance, a/NTSM [-]
The number of theoretical stages per meter NTSM [1/m] or its reciprocal HETP illustrates the power of providing mass transfer. The value depends on many variables and is typically measured with recommended test systems at total reflux. The number of theoretical stages NTS required for the separation duty is the output from the process design hence NTS/NTSM gives the necessary bed height, provided that the design of distributor and collector is done correctly.
One objective of our development work is to develop a structure with the most efficient surface; a packing where the surface area *a* necessary to provide a certain mass transfer capability *NTSM* is as small as possible for mainly two reasons:
- development towards the "ideal structure"
- its positive effect for pressure drop, void fraction, fouling behaviour etc.

The surface efficiency for separation performance is expressed by

$$\frac{a}{NTSM} \quad [-] \tag{15}$$

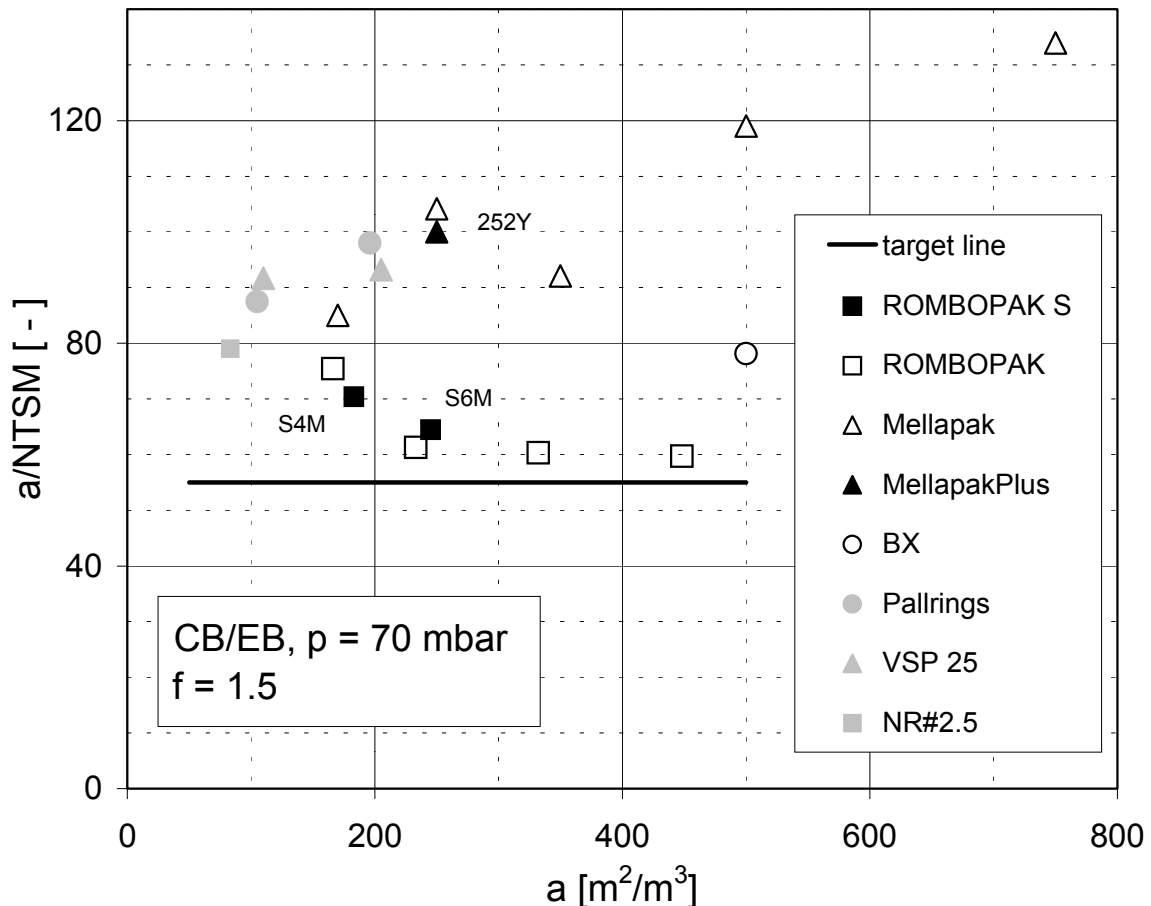In the following diagram values for different packing types are depicted versus *a*.

Figure 8: Values of a/NTSM (eq. 15) versus the specific surface a [2][4].

We can see that Rombopak has low values in the region of about 60, whereas the values for Mellapak lie in the region of 90 and more. The values achieved by Rombopak express its extraordinary and excellent wetting behaviour achieved from the grid structure, where the liquid is guided along the lamellas and the liquid surface is renewed at each node point (fig. 2). We currently see a target for the expected new Rombopak types in the region below 60.

The data from other suppliers were taken from their official brochures, where data of *a* are available.

OVERALL PERFORMANCE, N [-]

To distinguish between different internals the engineer currently has to consider three diagrams for each different packing type.

NTSM (HETP) vs. f

Δp vs. f

C vs. Ψ

In cases where all three criteria are of importance (at least all vacuum applications) ideally all criteria should be combined in order to allow the optimal choice of packing type. Several attempts were made to find descriptions which combine the a. m. criteria [5]. In the following we describe a new approach.

Importance of Δp

In applications where pressure drop is of importance the values of Δp and NTSM need to be regarded. The known ratio of Δp/NTSM has disadvantages. The value has to be calculated for a certain f-factor, and with changing slopes of pressure drop versus f-factor for different packing types and liquid loads we get a set of different numbers and not really an improvement in clarity. An overall performance number should be high for high performance and ideally be dimensionless. In our approach it is built up by putting NTSM into the denominator and the pressure drop into the numerator which becomes dimensionless with f^2. Hence we find

$$N = \frac{NTSM \left[\dfrac{1}{\text{m}}\right] \cdot f^2 [\text{Pa}]}{\Delta p \left[\dfrac{\text{Pa}}{\text{m}}\right]} \quad [-] \qquad (16)$$

Normally performance values are plotted against a capacity factor such as the f-factor. However the consideration of the maximum capacity should illustrate similarities for identical packing types. This can be obtained with f relative to the f-factor at flooding point:

$$x = \frac{f}{f_{\max}} \quad [-] \qquad (17)$$

As $f/f_{\max}$ tends towards unity, for all packing types N tends towards zero (infinite pressure drop at flooding point). For lower f-factors where Δp is proportional to about f^2 the values should lie on a plateau. At very low f-factors and liquid loading NTSM and as a consequence N tends to decrease because of the insufficient wetting of the packing.
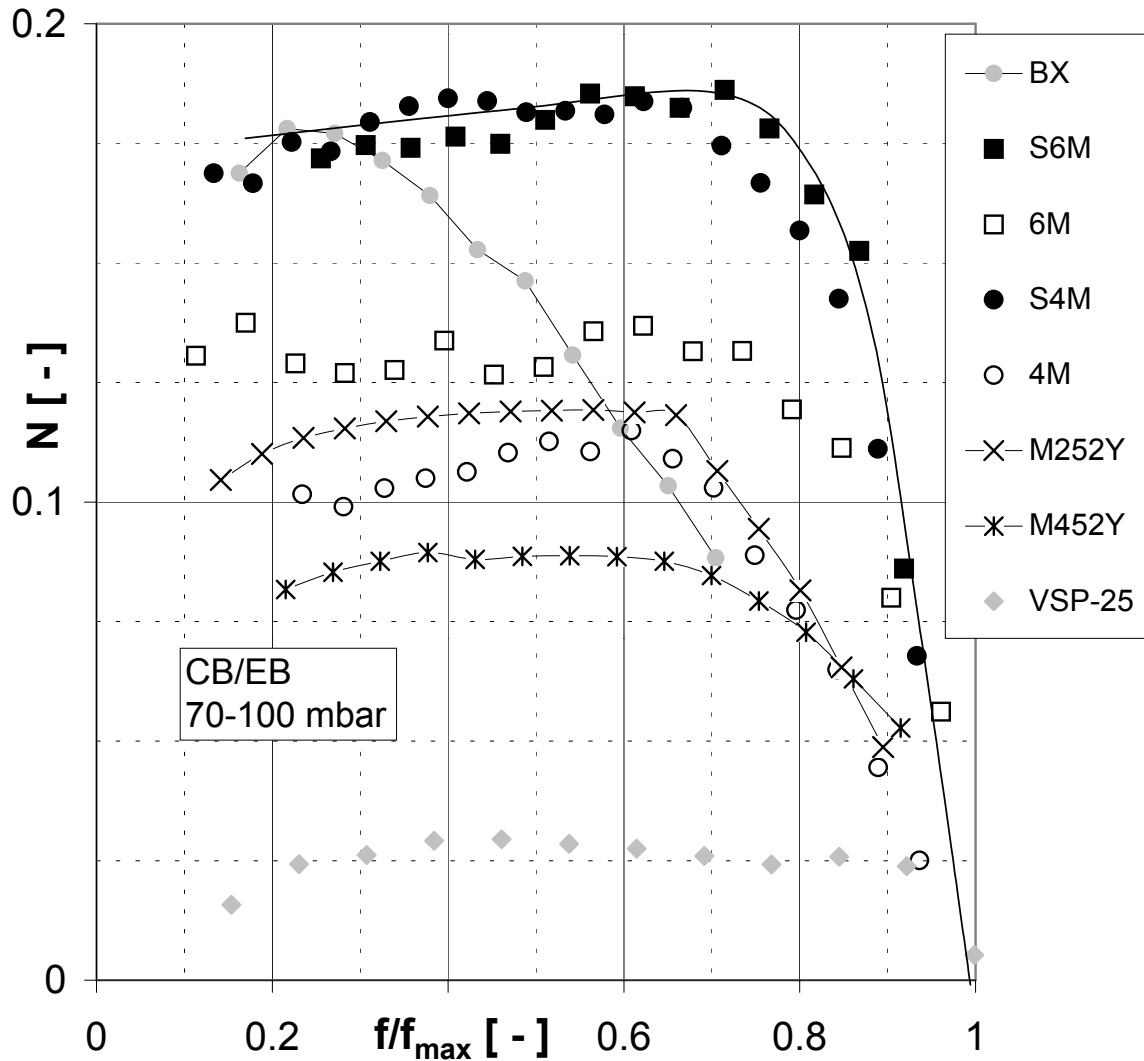
Figure 9: N (eq. 16) versus f/f$_{max}$.

The values are all obtained from the official vendor's brochures for the condition of about 60 to 100 mbar for the test system chlorobenzene / ethylbenzene. For Rombopak these have been verified with this test system at total reflux in columns ∅ 250 and 800 mm and bed heights between 2 and 4 m [2] [4]. For higher operating pressures the pressure drop becomes less important and this diagram looses its meaning. The engineer has to regard his operation region and to draw the diagram for the relevant conditions and packing types.

Non Importance of Δp
For higher pressure, respectively higher liquid load applications, pressure drop becomes less important. Then the usual approach of comparison of available *NTSM* and capacity from different packing types is sufficient. Here again the combination of the relevant parameters results in **one** diagram with a reasonable interpretation.
By simplification we assume that the column height is about proportional to 1/NTSM, whereas the column cross section is proportional to 1/f or 1/C. Hence the column volume is inversely proportional to the product of NTSM and C. It is unfortunately not dimensionless, but it can be interpreted as the reciprocal of a time, which is

proportional to the residence time.

$$NTSM \cdot C = \frac{1}{\tau} \quad [1/\text{s}] \tag{18}$$

The higher the values are, the smaller the columns become. In the following diagram (fig. 10) the values of $NTSM \cdot C$ are depicted versus the specific surface a.
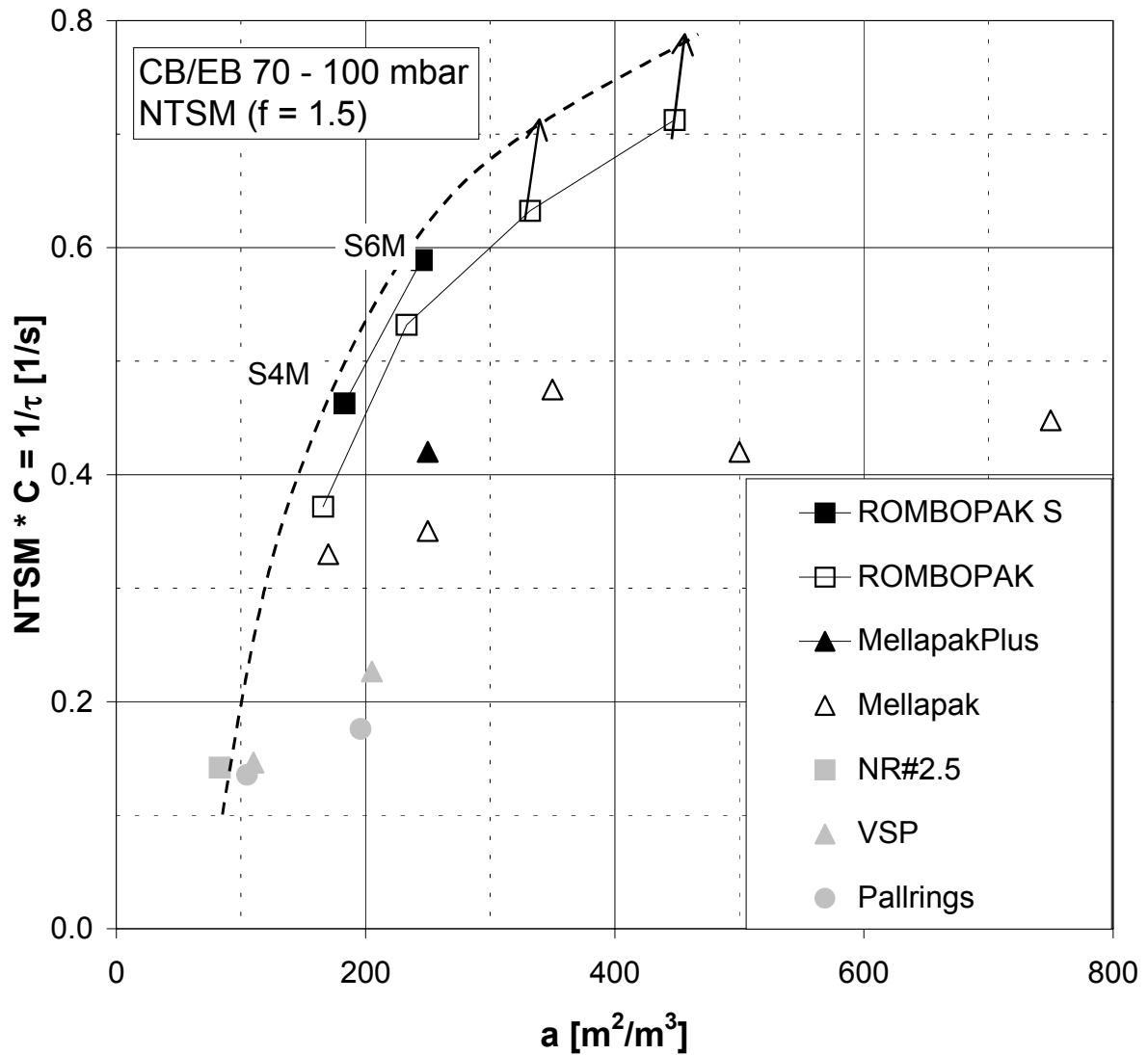

Figure 10: NTSM · C (eq. 18) versus a; same data as in figure 9.

We can see the improvements obtained by the new high performance packing types and can clearly identify the principle curves being followed from the different packing types. Arrows indicate the direction of further development work (targets) for Rombopak S.

OUTLOOK

The criteria mentioned before and the comparison with theoretical limitations show that further improvements are possible and can be expected. Progress needs the rigorous analysis of all effects by means of modern tools like CFD. In the future we will add to our research work from one single phase gas flow analysis, the analysis of liquid flow on structured surfaces with the aim of further improving NTSM and C. With progress in software capability we might come to CFD analysis of two phase countercurrent flow in structured packings. This would allow the prediction of flooding points.

With respect to the characteristic numbers we intend to implement a model for the surface efficiency (to derive N_a in a similar way as for N_p and N_c) taking into account mass transfer on a plate and if reasonable to combine N_p, N_c and N_a to one characteristic number describing the performance completely.

NOMENCLATURE

A	surface	$[m^2]$
a	specific surface area	$[m^2/m^3]$
$a/NTSM$	surface efficiency	[-]
C	capacity	[m/s]
d_c	drop diameter	[m]
d_h	hydraulic diameter	[m]
f	f-factor	$\sqrt{Pa}$
f_{max}	f-factor at flooding point (Δp = 12 mbar/m)	$\sqrt{Pa}$
$\dot{G}$	vapour mass flow rate	[kg/h]
$\dot{L}$	liquid mass flow rate	[kg/h]
N	overall efficiency factor	[-]
$NTSM$	number of theoretical stages	[1/m]
N_a	surface efficiency factor	[-]
N_c	capacity factor	[-]
N_p	pressure drop factor	[-]
p	pressure	[Pa]
Δp	pressure drop	[mbar/m]
s	spacing	[m]
U	circumference	[m]
v_g	gas velocity	[m/s]

v_l	specific liquid load	[m^3/m^2 h]
η	dynamic viscosity	[Pa s]
ρ_g	gas density	[kg/m^3]
ρ_l	liquid density	[kg/m^3]
σ	surface tension (g-l)	[N/m]
τ	residence time	[s]
υ	kinematic viscosity	[m^2/s]
ψ	Flow parameter	[-]
ζ	pressure drop coefficient	[-]

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