A NEW METHOD TO PREDICT THE SUSCEPTIBILITY TO FORM MALDISTRIBUTION IN PACKED COLUMNS BASED ON PRESSURE DROP CORRELATIONS

Markus Duss
Sulzer Chemtech Ltd., Sulzer-Allee 48, P.O.Box 65, CH-8404 Winterthur, Switzerland
E-mail address: markus.duss@sulzer.com

This paper presents a new method to predict the susceptibility to form maldistribution in packed columns. The method is based solely on pressure drop correlations; no other data are required. Three key figures are introduced, which are: the potentially available force to shift liquid, the vapour maldistribution susceptibility factor and the driving force to induce maldistribution. These three key figures result from an extrapolation and from derivates of the pressure drop correlation.

KEYWORDS: maldistribution, random and structured packing, sensitivity, susceptibility, pressure drop

INTRODUCTION

Structured and random packings are widely used in separation columns in the pharmaceutical, chemical and oil & gas industry. In order to minimise the investment cost, new columns are being designed to be operated at their maximum capacity, with little or no hydraulic safety margin. In such designed columns the pressure drop is relatively high and therefore the forces to induce maldistribution might be comparably high.

Methods to calculate the impact of a given maldistribution on a certain separation task have been developed [1], [2]. These methods calculate the 'apparent loss of the number of theoretical stage' with liquid maldistribution and hence a separation can be judged whether it acts sensitively on an assumed maldistribution. However, there is no method available to quantify the risk whether a system shows an increased tendency to form maldistribution. Methods such as computational fluid dynamic (CFD) are predestined to quantify maldistribution in a two phase system, but due to the immensely computational power required, there is still a long way to go until this ambitious target will be achieved. This paper introduces a simple method which allows the derivation of key figures to qualify the susceptibility of a system to form maldistribution. The only premise is the availability of an accurate correlation to calculate the pressure drop of the considered packing.

PRESSURE DROP IN PACKED COLUMNS

The local pressure drop in packings is depending on the packing geometry, on velocities of vapour and liquid, on the physical properties such as density and viscosity of each phase and on the liquid surface tension.

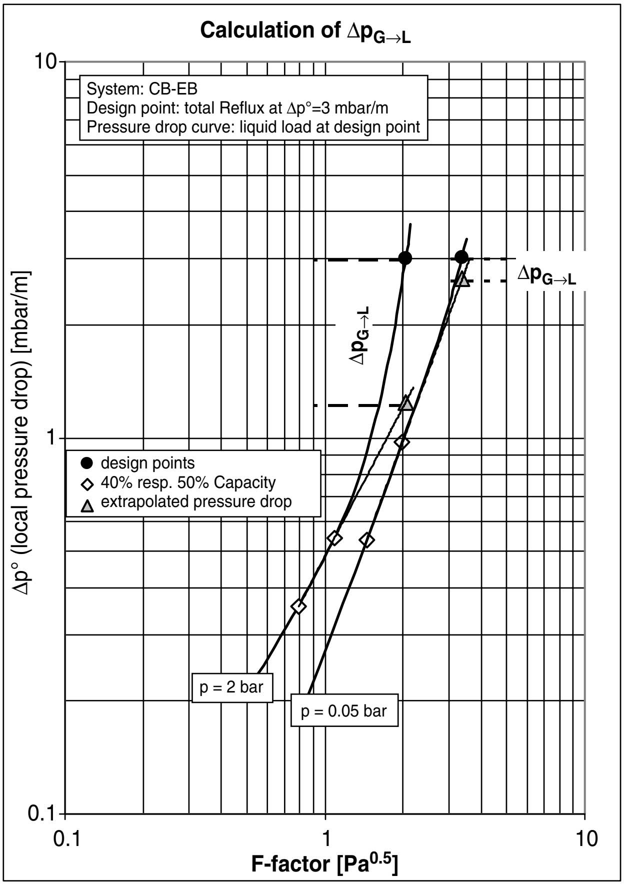

Figure 1.

A typical shape of pressure drop curves is given in Figure 1, where pressure drop is shown as a function of the F-factor *Fv*, which is the square root of twice the dynamic head of the vapour phase. In all figures given below, only the F-factor is varied; the liquid load remains constant for the individual curves. The indicated points in Figure 2 are not experimental points but calculated with a pressure drop correlation. The methodology used is described by Spiegel and Meier [3] and was implemented in the program SULPAK®, a freely available program. The pressure drop is expected to be proportional to the vapour velocity squared for a fully developed turbulent flow regime and directly proportional to the velocity for a laminar regime. Therefore, the slope of the pressure drop

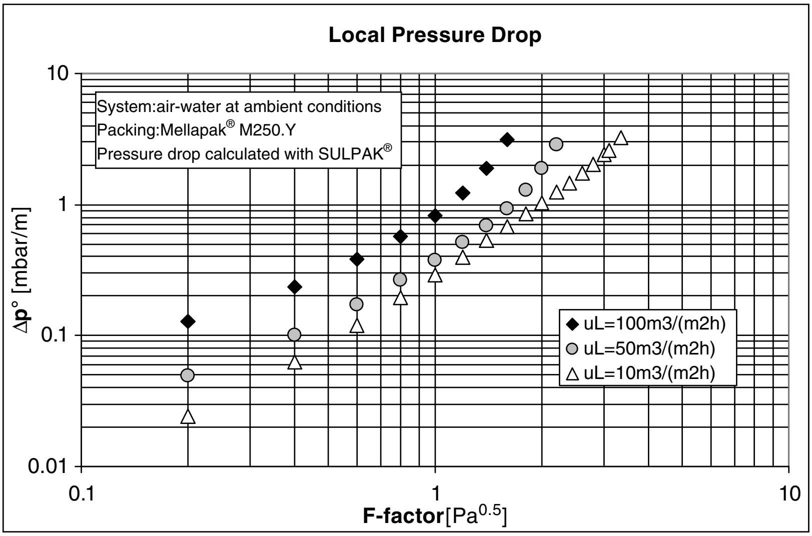

Figure 2.

curve might decrease at low F-factors, depending on the Reynolds number of the vapour. This is accounted for by the friction factor, which is a function of the vapour Reynolds number.

Up to a certain dynamic head the liquid hold-up is unaffected by the vapour and thus it remains constant. The point where hold-up starts to increase due to interaction with the vapour, is called the loading point and the pressure drop increases more than proportionally to the vapour velocity squared.

At a certain local pressure drop, entrainment of liquid increases drastically and the liquid phase is not able to flow counter currently to the vapour: the column cannot be operated stably at this point and this is referred to as flooding. The maximum F-factor, where the column still can be operated stably is referred to as 100% capacity. Spiegel and Meier [3] defined 100% capacity to be at 12 mbar/m of local pressure drop for structured packings. This definition can also be applied to random packing. It should be pointed out that at 100% capacity the efficiency is drastically reduced and therefore, columns are not operated at this point. The recommended design guidelines depend on the type of packing used: Mellapak® (standard structured packing), MellapkPlus® (high capacity structured packing) and random packings have different recommended maximum design limits, referring to maximum recommended local pressure drop or capacity, respectively. At higher than the maximum recommended capacity a significantly reduction in efficiency might result. The capacity is defined as the percentage of liquid and vapour rates compared to the rates at 100% capacity at constant liquid to vapour ratio. Therefore, a column which is operated at e.g. 50% capacity can increase both vapour and liquid flow rates by a factor of 2 until 100% capacity is reached.

INFLUENCE OF VAPOUR FLOW ON LIQUID MALDISTRIBUTION

When a packed column is operated below the loading point, by definition the liquid hold-up is not influenced by the vapour and the force exerted by the vapour on the liquid is negligible. Hence, it is assumed that the vapour phase is not influencing the formation of liquid maldistribution below the loading point. Above the loading point the liquid hold-up is increased due to the force exerted from the vapour and thus, this force is able to move or shift liquid inside the packing. Therefore, the higher the force of the vapour exerted on the liquid, the higher the risk of liquid maldistribution induced by the vapour. This force in terms of pressure drop, $\Delta p_{G\to L}$, can be calculated as the difference of the total local pressure drop, Δp°, and the hypothetical pressure drop without vapour-liquid interaction, Δp_{extr}. The latter can be calculated by extrapolation from below the loading point, assuming that all relevant physical properties remain constant.

$$\Delta p_{G\to L} = \Delta p^o - \Delta p_{extr} \tag{1a}$$

$$\Delta p^o = \Delta p(Packing, u_L^o, u_G^o, \eta_L^o, \eta_G^o, \rho_L^o, \rho_G^o, \sigma^o) \tag{1b}$$

The extrapolation from below the loading point should exclude the vapour-liquid interaction but should account for the change of the friction factor. Depending on the correlation used to calculate the pressure drop, this might not be easily apparent, in particular if the correlation itself is not available to the user but only the resulting total local pressure drop. Therefore, the following procedure (as illustrated with Figure 1) is used to calculate the extrapolated pressure drop Δp_{extr}:

1. Calculate F-factor Fv° and local pressure drop Δp° at design conditions.
2. Determine pressure drop and F-factor at 40% and 50% capacity *at design liquid load*.
3. Calculate extrapolated pressure drop Δp_{extr} at design F-factor Fv° as follows:

$$\Delta p_{extr} = a \cdot (F\nu^o)^b \tag{2a}$$

$$a = \Delta p_{40\%} \cdot (F\nu_{40\%})^{-b} \tag{2b}$$

$$b = \frac{\log\Delta p_{50\%} - \log\Delta p_{40\%}}{\log F\nu_{50\%} - \log F\nu_{40\%}} \tag{2c}$$

4. Evaluate pressure drop due to vapour-liquid interaction, $\Delta p_{G\to L}$, according to equation (1a).

$\Delta p_{G\to L}$ must be interpreted as a potentially available force to shift liquid. How it will act on the liquid phase depends on the physical properties and the packing geometry. When the operating point is below 50% capacity it is assumed that it is below the loading point and hence no force is exerted by the vapour on the liquid which is able to shift liquid.

Figure 1 shows two different pressure drop curves for the system chloro benzene/ ethyl benzene (CB/EB). The curves are calculated for distillation columns with different operating pressures, i.e. $p_1 = 0.05$ bar and $p_2 = 2$ bar and with the assumption that both columns are designed at 3 mbar/m local pressure drop and at total reflux. The curves retrieved in Figure 1 were calculated for the packing type Mellapak® M250.Y using the program SULPAK® and the physical properties used are those of pure EB. The resulting pressure drop due to vapourliquid interaction, $\Delta p_{G \rightarrow L}$, differs significantly for the two cases, even though both columns are designed at the same local pressure drop of $\Delta p^{\circ} = 3$ mbar/m. Whereas for the vacuum application the available specific force to shift liquid, $\Delta p_{G \rightarrow L}$, is approx. 0.4 mbar/m, for the column operated at $p = 2$ bar it is more than 1.7 mbar/m. The potentially available force to shift liquid is more than a factor of 4 higher in the pressure column than in the vacuum distillation column. To which extent $\Delta p_{G \rightarrow L}$ does induce a liquid maldistribution depends on the physical properties and the flow regime; this will be discussed below.

Figure 3 shows the resulting pressure drop due to vapour-liquid interaction, $\Delta p_{G \rightarrow L}$, for the system air-water with variable F-factor and for 3 different liquid loads. The higher the liquid load the sharper is the increase in pressure drop $\Delta p_{G \rightarrow L}$ above the loading point. The contribution of the vapour-liquid interaction to the total measured pressure drop, Δp°, is significantly higher with increased liquid loads.

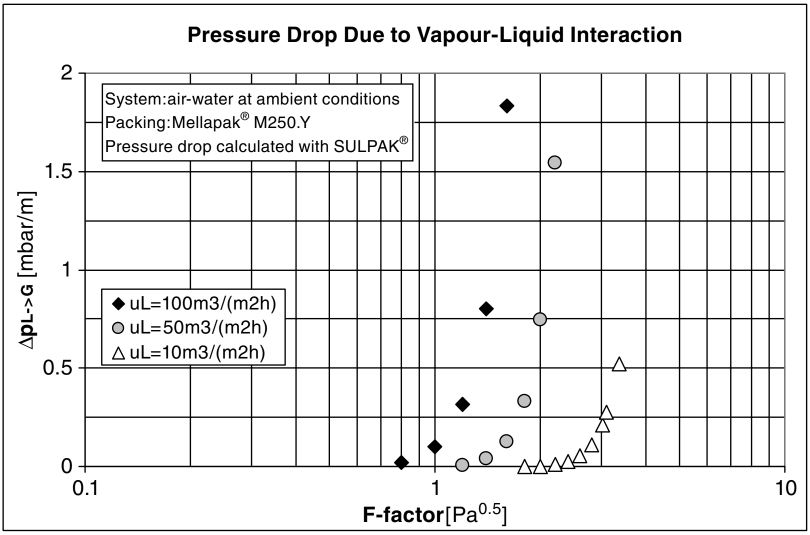

Figure 3.

VAPOUR MALDISTRIBUTION SUSCEPTIBILITY

Common maldistribution sensitivity analyses to calculate the impact of maldistribution on the separation assume that the column is divided into two equal parts by an imaginary impermeable wall [1], [2]. A certain liquid maldistribution is then assumed at the top of the column and the vapour is split evenly and fed to the bottom of the section in consideration. The two liquid and the two vapour streams leaving the section are mixed in order to get the resulting concentration in the liquid and vapour streams, respectively. Both columns are simulated with the number of theoretical stages (NTS) according to the design. The apparent loss of the NTS compared to an ideal column with no maldistribution is calculated by reducing the NTS in the ideal column, so the same product concentrations will be achieved as the mixed stream leaving the section with the assumed maldistribution.

Some of these assumptions might not be adequate, depending on the operating conditions and the physical properties of the system. The required force to shift liquid is high compared to the force required to shift vapour. Therefore, the following assumption is postulated: vapour is distributed across the cross sectional area of the column such that the local pressure drop is equal at each point, i.e. the radial pressure gradient is zero. Thus, assuming the column is split into two equal parts but now with an imaginary vapour-permeable wall, it follows for an infinitesimal change in liquid velocity, when the physical properties remain constant:

$$\Delta p(u_L^o + du_L, u_G^o - du_G) = \Delta p(u_L^o - du_L, u_G^o + du_G) \tag{3}$$

and from the partial derivates of equation (3) follows:

$$\frac{\partial \Delta p}{\partial u_L} \cdot du_L - \frac{\partial \Delta p}{\partial u_G} \cdot du_G = 0 \tag{4}$$

Rearranging equation (4) yields:

$$\frac{du_G}{du_L} = \frac{\dfrac{\partial \Delta p}{\partial u_L}}{\dfrac{\partial \Delta p}{\partial u_G}} \tag{5}$$

And the vapour maldistribution susceptibility factor S_G is defined for a specific design point:

$$S_G = \frac{\dfrac{du_G}{u_G^o}}{\dfrac{du_L}{u_L^o}} = \frac{\dfrac{\partial \Delta p}{\partial u_L}}{\dfrac{\partial \Delta p}{\partial u_G}} \cdot \frac{u_L^o}{u_G^o} \tag{6}$$

The vapour maldistribution susceptibility factor S_G can be interpreted simply as the percentage of vapour maldistribution due to one percent of liquid maldistribution with constant physical properties (and assuming the radial pressure gradient to be zero). This is also the proposed solution to calculate S_G numerically.

The susceptibility factor, S_G, depends strongly on the physical properties and on the operating conditions and might therefore change significantly with changing physical properties and velocities along the column height. Figure 4 shows the resulting susceptibility factor S_G for air-water at 20°C with varying F-factor and for 3 different liquid loads using the pressure drop correlation of SUKLPAK®. According to Figure 4 the influence of the liquid maldistribution on the vapour maldistribution is below 0.1 for a specific liquid load of $10\mathrm{m}^3/(\mathrm{m}^2 \cdot \mathrm{h})$ of water: thus it is negligible. When the specific liquid load is increased to $50\mathrm{m}^3/(\mathrm{m}^2 \cdot \mathrm{h})$ the susceptibility of the vapour to evade the liquid is increased and S_G increases. When the liquid load is increased further to $100\mathrm{m}^3/(\mathrm{m}^2 \cdot \mathrm{h})$, the vapour maldistribution susceptibility factor S_G is increased significantly and the vapour maldistribution might become the dominant factor for maldistribution. The shape of the three curves in Figure 4 indicates that the susceptibility is increased with decreasing F-factors, i.e. when the local pressure drop is small. For liquid loads of 10 and $50\mathrm{m}^3/(\mathrm{m}^2 \cdot \mathrm{h})$ the susceptibility factor S_G has a minimum which is close to the loading point. However, at a liquid load of $100\mathrm{m}^3/(\mathrm{m}^2 \cdot \mathrm{h})$ the pressure drop correlation does not predict such a minimum susceptibility.

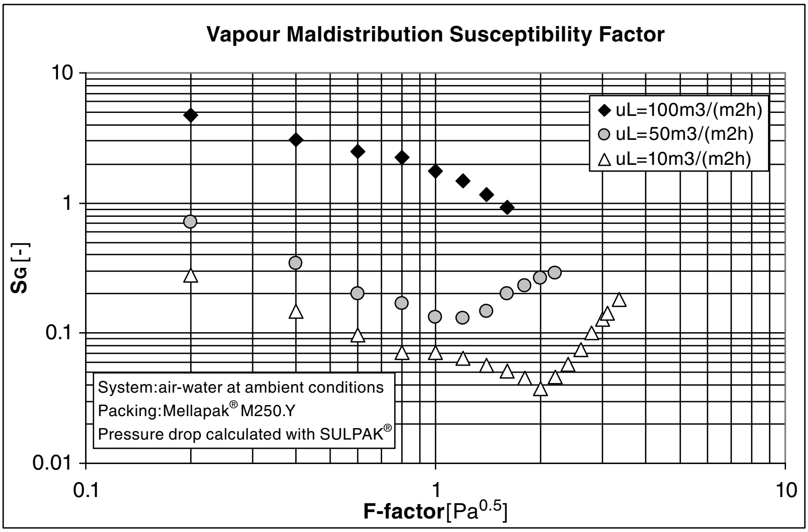

Figure 4.

Attention must be paid to the accuracy of the correlation when the numbers for S_G are taken absolutely. Since pressure drop correlations contain often empirical correction factors accounting for measured phenomena, the transition when these factors are applied might not be always smooth. Indeed, methods like the calculation of S_G could be used to check for the consistency of the correlations.

DRIVING FORCE TO INDUCE MALDISTRIBUTION

Two key figures have been derived so far: $\Delta p_{G \rightarrow L}$, a pressure drop difference to characterise the potentially available force to shift liquid and S_G, which quantifies the *vapour* maldistribution resulting from a given *liquid* maldistribution. These two key figures do not allow us to judge whether a once induced maldistribution is stable or whether it will randomly distribute. The latter would not necessarily lead to a continuous increase in maldistribution with increasing packed bed height. However, experience tells us, that liquid collectors and redistributors are required after a certain packed height to maintain the efficiency. This is an indication that maldistribution may be formed systematically with increasing packing height.

The definition of the third key figure is an attempt to qualify the tendency of a systematic formation of maldistribution: the driving force to induce maldistribution. It must be underlined that the accuracy of the pressure drop correlations may not always be adequate enough to retrieve values with a sound meaning. However, the concept of the driving force to form maldistribution is helpful and is as follows: A system tends to minimise its pressure drop. When the resulting pressure drop with maldistribution is lower compared to an evenly distributed state, then a once induced maldistribution is stable and will become even more severe with increasing flow path length, i.e. with increasing packed height.

The following method is proposed to determine the specific driving force to form maldistribution, in terms of a pressure drop per height: Again, the column is split into two equal parts assuming an imaginary vapourpermeable wall. The resulting pressure drop with an assumed liquid maldistribution, Δu_L, and with the vapour distributed to achieve equal pressure drops in both parts of the column is calculated. The difference between the so retrieved pressure drop and the design pressure drop (without maldistribution) is used to define the force to induce maldistribution. Applying the change in vapour velocity with a change in liquid velocity according to equation (6) and normalising for the design liquid velocity, $u_L{}^{\circ}$, the driving force to induce maldistribution, Δp_{Ind}, is defined as:

$$\Delta p_{Ind} = \lim_{\Delta u_L \to 0} \frac{\Delta p\left(u_L^o + \Delta u_L, u_G^o - S_G \cdot \frac{u_G^o}{u_L^o} \Delta u_L\right) - \Delta p^o}{\left(\frac{\Delta u_L}{u_L^o}\right)^2} \qquad (7)$$

When evolving equation (7) with a Taylor series about the design point, the first derivatives cancel each other due to the definition of the vapour maldistribution susceptibility factor, S_G.

Therefore, it follows:

$$\Delta p_{Ind} = \frac{\frac{\partial^2 \Delta p}{\partial u_L^2} \cdot du_L^2 - 2 \cdot \frac{\partial^2 \Delta p}{\partial u_L \partial u_G} du_L \cdot S_G \cdot \frac{u_G^o}{u_L^o} du_L + \frac{\partial^2 \Delta p}{\partial u_G^2} \cdot \left(S_G \cdot \frac{u_G^o}{u_L^o} du_L \right)^2}{2 \cdot \left(\frac{du_L}{u_L^o} \right)^2} \tag{8}$$

Rearranging equation (8) yields:

$$\Delta p_{Ind} = \frac{u^o_{L^2}}{2} \cdot \left(\frac{\partial^2 \Delta p}{\partial u_L^2} - 2 \cdot \frac{\partial^2 \Delta p}{\partial u_L \partial u_G} \cdot S_G \cdot \frac{u_G^o}{u_L^o} + \frac{\partial^2 \Delta p}{\partial u_G^2} \cdot \left(S_G \cdot \frac{u_G^o}{u_L^o} \right)^2 \right) \tag{9}$$

Equation (9) can be interpreted as a measure for the stability of the liquid film and hence whether a system likes to form maldistribution or not. The force to form or to even out maldistribution is proportional to Δp_{Ind}. If the obtained result is negative, then the system can reduce its pressure drop by inducing maldistribution. The higher this gain is, the more likely maldistribution will be induced with increasing flow path length. For positive values of Δp_{Ind} the opposite holds: the system tends to adjust imbalances and maldistribution will occur less likely.

The difference in pressure drop with and without maldistribution is small and problems might occur when solving equation (9) numerically. Therefore, the following modification of the definition (7) is proposed: the driving force to induce maldistribution $\Delta p_{Ind(M10\%)}$ is defined according to equation (7) but with a liquid maldistribution resulting in $\Delta u_L / u_L^o = 0.1$. Thus, this modified definition results in:

$$\Delta p_{Ind(M10\%)} = \frac{\Delta p_{M10\%} - \Delta p^o}{0.01} \tag{10a}$$

with the constraint

$$\Delta p_{M10\%} = \Delta p(1.1 \cdot u_L^o, u_G^o - \Delta u_G) = \Delta p(0.9 \cdot u_L^o, u_G^o + \Delta u_G) \tag{10b}$$

Solving equation (10b) achieves the pressure drop with 10% liquid maldistribution. This is done iteratively by varying Δu_G in equation (10b) until equal pressure drops are achieved.

The value of the specific driving force according to equation (10a), $\Delta p_{Ind(M10\%)}$, might deviate somewhat from equation (9) but it can be easily obtained numerically. The conclusion remains the same: when $\Delta p_{Ind(M10\%)}$ is negative, the system can reduce its pressure drop by inducing maldistribution; when the value is positive the resulting pressure drop is increased and the system tends to adjust imbalances of liquid and vapour velocities.

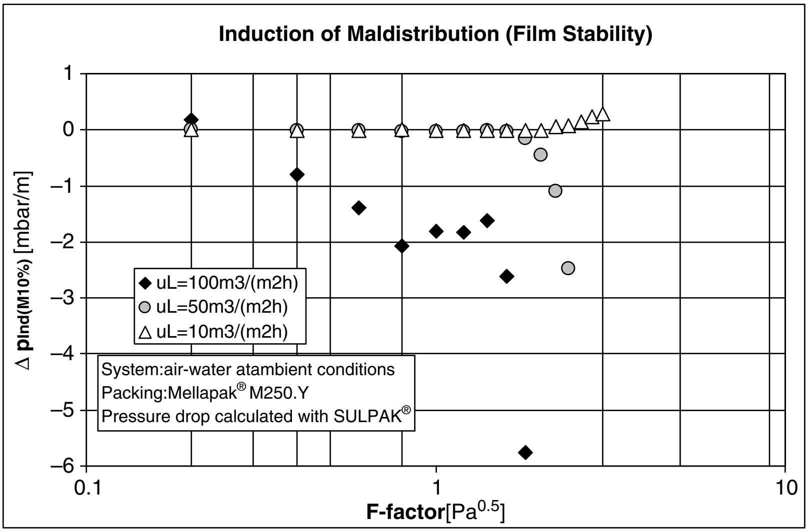

Figure 5.

Figure 5 shows the driving force to induce maldistribution $\Delta p_{Ind(M10\%)}$ for the air-water example. For a liquid load of 10 $m^3/(m^2 \cdot h)$ the driving force is small and above the loading point the derived values from the pressure drop correlation even predict a slight increase in pressure drop with maldistribution. At a specific liquid load of 50 $m^3/(m^2 \cdot h)$ the driving force is small but increases sharply when approaching a local pressure drop of $\Delta p^o = 3\mathrm{mbar/m}$ (Figure 1). At a specific liquid load of 100 $m^3/(m^2 \cdot h)$ the driving force is remarkably higher, even when the local pressure drop Δp^o is still small.

The impact of the gained pressure drop on the liquid is difficult to describe quantitatively and might depend strongly on $\Delta p_{G \to L}$ and on the physical properties. This will be discussed in the chapter below.

INTERPRETATION OF THE KEY FIGURES

The three key figures derived from pressure drop correlations allow characterising a system: this is called a 'maldistribution susceptibility analysis'. However, the key figures do not allow quantifying the formation of maldistribution along the radial or axial direction a priori and an interpretation based on empirical knowledge is still required. The physical properties, such as density, viscosity and surface tension must be included in the interpretation, as well as the influence of the column diameter. The outcome of the analysis and of the interpretation will only allow to judge whether the system is susceptible to form maldistribution, resulting in a recommendation for the maximum height for a packed bed before a liquid redistribution system is required. However, this is still a heuristic approach and is not discussed in this paper.

When both, the potential force to shift liquid ($\Delta p_{G \rightarrow L}$) and the driving force to induce maldistribution ($\Delta p_{Ind(M10\%)}$) are high, then the danger of maldistribution being formed is increased. The system can easily make use of the potential force to shift liquid. If additionally the system shows high vapour maldistribution susceptibility (S_G), the formation of maldistribution can be severe. However, the impact on the loss of efficiency depends also on the operating and design conditions, i.e. on the stripping factor and number of NTS per bed. As it can be seen from the Figures 3 to 5, all three key figures indicate that maldistribution is more likely formed with increasing liquid load and the forces which acts on the liquid increase strongly above the loading point.

One of the assumptions made in order to retrieve the key figures was, that no force is required to shift the vapour. This assumption is due to the fact that the vapour phase is the continuous phase and that the viscosity is low. The latter holds also for the liquid phase: with decreasing liquid viscosity the friction is decreased and hence with a given force to shift liquid ($\Delta p_{G \rightarrow L}$) and a given force to induce maldistribution (Δp_{Ind}) the volume of shifted liquid is also increased and results in an increased maldistribution. A similar conclusion can be drawn in respect to the liquid density: the lower the density the more liquid can be shifted in terms of volume. Further more it can be expected, that with increasing thickness of the liquid film, more liquid can be shifted with a given force acting on the film. Concerning surface tension it seems less obvious how the susceptibility to form maldistribution might be influenced. The net change of the interfacial area between liquid and vapour due to maldistribution is small. When the surface tension decreases, small droplets can be easily formed and liquid might be shifted in such a way. This is no explanation for a higher risk of a hydraulic maldistribution formation, since these droplets are shifted into regions of higher gas velocity and hence, this would lead to an adjustment of the imbalances of the liquid and vapour velocities. But this would result in axial back mixing and therefore in loss in driving force, what is also interpreted as a loss in packing efficiency, in a similar way as liquid and vapour maldistribution manifests itself as apparent loss in efficiency. Experimental data clearly indicate that surface tension has an impact on the capacity limit in packed columns. However, the influence on the mobility of the liquid phase and thus on the formation of maldistribution is not yet investigated.

CONCLUSION AND OUTLOOK

A new method to characterise the risk of the formation of maldistribution in packed columns is given by introducing three key figures: $\Delta p_{G \rightarrow L}$, a potentially available force to shift liquid; S_G the vapour maldistribution susceptibility factor which indicates the percentage of vapour maldistribution due to one percent of liquid maldistribution; and Δp_{Ind}, which is the driving force to induce maldistribution. This method is referred to as maldistribution susceptibility analysis.

When operating packed columns close to the hydraulic limits, this might results in increased forces to form maldistribution. On the other hand, when operating packed columns at very low F-factors, the vapour susceptibility factor, S_G, might be very high and thus vapour maldistribution induced by an initial liquid maldistribution might become an important factor to be considered. The maldistribution susceptibility analysis introduced in this paper is a simple attempt to judge such risks concerning hydraulic maldistribution.

The method cannot be used to quantify maldistribution a priori but the key figures need to be interpreted. The physical properties influence the key figures since they influence the pressure drop. However, how the physical properties influence the maldistribution quantitatively, i.e. how the key figures can be interpreted is not yet investigated thoroughly. In particular the influence of liquid viscosity, film Reynolds number and surface tension needs further clarification, as well as the influence of the column diameter.

From the key figures for the system air-water it was concluded, that maldistribution is more likely formed when the liquid load is increased. The liquid properties at boiling point conditions (such as density, viscosity and surface tension) tend to decrease with increasing operating pressure and from the interpretation of the key figures it was expected that this will result in increased maldistribution susceptibility. Therefore, it can be assumed that pressure distillation applications show a significantly increased susceptibility to form maldistribution compared to vacuum applications, particularly when columns are operated above the loading point.

NOMENCLATURE

Fv	[Pa$^{0.5}$]	F-factor $= u_G(\rho_G)^{0.5}$
NTS	[-]	Number of theoretical stages
u	[m/s]	Superficial velocity
S_G	[-]	Vapour maldistribution susceptibility factor
Δp	[mbar/m]	Local pressure drop
Δp_{extr}	[mbar/m]	Hypothetical local pressure drop without vapour-liquid interaction
$\Delta p_{G\rightarrow L}$	[mbar/m]	Potentially available specific force to shift liquid
Δp_{Ind}	[mbar/m]	Specific driving force to induce maldistribution
$\Delta p_{Ind(M10\%)}$	[mbar/m]	Specific driving force to induce maldistribution based on $\Delta u_L/u_L^o = 0.1$
$\Delta p_{M10\%}$	[mbar/m]	pressure drop with liquid maldistribution $\Delta u_L/u_L^o = 0.1$

GREEK SYMBOLS

ρ	[kg/m^3]	Density
η	[Pa · s]	Viscosity
ρ	[kg/m^3]	Density
σ	[N/m]	Surface tension

SUBSCRIPTS/SUPERSCRIPTS

G	vapour, gas phase
L	liquid phase
o	design condition without maldistribution

LITERATURE CITED

1. Yuan, H. and Spiegel, L., Theoretical and Experimental Investigation of the Influence of Maldistribution on the Performance of Packed Columns at Partial Reflux, Chem.-Ing.-Tech. MS 1025/82.
2. Billingham, J.F. and Lockett, M.J; A Simple Method to Assess the Sensitivity of Packed Distillation Columns to Maldistribution, Trans IChemE, Vol 80, Part A, May 2002.
3. Spiegel, L. and Meier, W., A Generalized Pressure Drop Model for Structured Packing, International Conference on Distillation and Absorption, Birmingham, Sept. 7–9, 1992.