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Application of the Wallis Plot for the Determination of the Loading Limits of Structured Packings and Sandwich Packings

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Structured packings are widely used in many separation units in the chemical process industry. One of the innovative modifications of structured packings is the so-called sandwich packings, which consist of two packing layers with different geometrical surface area. Fluid dynamic parameters, such as the flooding point, are essential for the design of packed columns. The Wallis plot is an empirical method to provide a flooding point correlation based on experimental data. In the present work, experimental results obtained with common structured packings manufactured by Montz and Sulzer as well as with sandwich packings manufactured by Montz were used. From the pressure drop data for both packing types, the gas and liquid loads under flooding conditions were determined. Parameters of the Wallis equation were adapted, and a correlation was proposed allowing the loading limits of structured packings and sandwich packings to be described in a reliable way as functions of the geometrical surface area, declination angle to the vertical as well as physical properties. The Wallis equation was implemented into a fluid dynamic model for the description of the pressure drop of sandwich packings (Brinkmann et al., 2012). By this way, the range of application of the model was extended and the predictivity improved.

1. Introduction

In the process industry, packed columns are used in a variety of fluid separation operations, e.g. in distillation and absorption, in order to create a targeted flow pattern of two-phase systems (Yazgi and Kenig, 2013). Due to the high energy requirements of separation processes, the interest on their optimisation is vital. In particular, column internals have permanently been the focus of investigations. In this regard, the progress in the design of corrugated sheet structured packings has been impressive, aiming at improved capacity and efficiency of separation units.

Among the new developments are the so-called high performance structured packings (e.g., MONTZ-Pak, Type M) and sandwich packings. In the high performance packings, pressure drop is reduced by bending the lower part of corrugated channels from 45 to 90°. The sandwich packings consist of two alternating layers of industrially available standard packings with different specific surface (Figure 1, left), one with lower (the so-called hold-up layer) and another with higher (the so-called de-entrainment layer) capacity (Jödecke et al., 2006). Such packings are typically operated between the flooding points of the hold-up layer and de-entrainment layer. Above the hold-up layer, a froth sub-layer with high separation efficiency due to intensified phase mixing is formed (Brinkmann et al., 2009). In the upper section of the de-entrainment layer, film-like flow patterns can be observed (Figure 1, right). In Figure 2, the top view of both layers is shown together with some downcomers integrated in the hold-up layer. The downcomers help to establish an improved, even distribution of the froth over the column cross-section. The latter also prevents liquid maldistribution, and hence, additional liquid distributors are not required (Jödecke et al., 2006).

Apart from the application of sandwich packings in new columns, they are inserted in revamps of existing columns. Metzen et al. (2010) showed that the integration of sandwich packings increases capacity while keeping the same efficiency. For this reason, sandwich packings are advantageous with respect to energy

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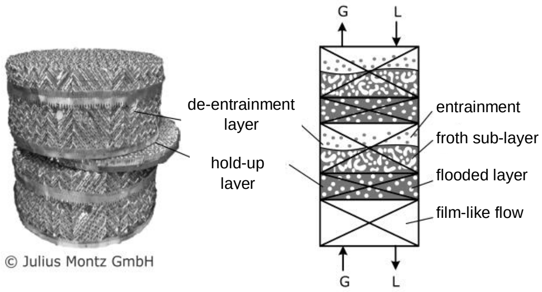

Figure 1: Sandwich packings: Photo (left) and schematic representation (right)

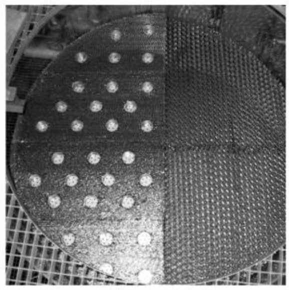

Figure 2: Top view of a sandwich packing with downcomers in the hold-up layer at the left side

In the conventional operating range of structured packings, a countercurrent flow of a falling liquid film with upflowing vapour is established. With increasing gas velocity, the interactions of both phases become more intensive and pressure drop grows. In Figure 3, showing a typical pressure drop profile, the intensification of the interactions is expressed by a slop change at the loading point. At flooding conditions, the pressure drop rises rapidly, and the countercurrent flow collapses.
Brinkmann et al. (2009) compared the pressure drop characteristics of conventional packings and sandwich packings. It was shown that the characteristic pressure drop and the loading limits of sandwich packings can be derived based on the pressure drop of structured packings, which is qualitatively shown in Figure 4. However, the gas load at the flooding point of the de-entrainment layer is shifted to lower values.

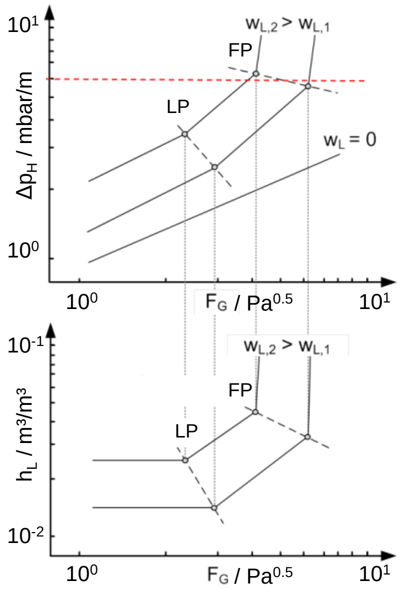

Figure 3: Typical structured packing profiles of pressure drop (above) and hold-up (below)

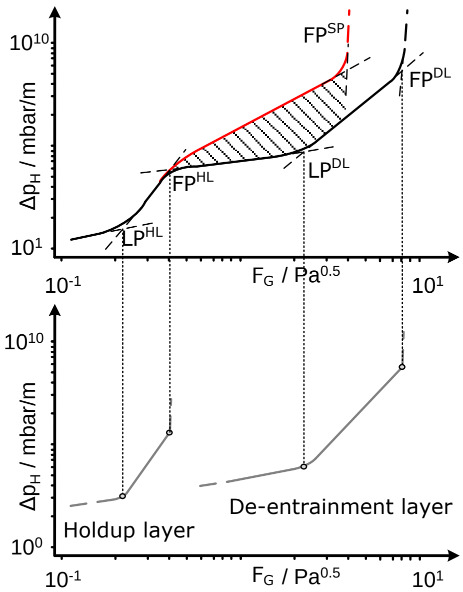

Figure 4: Pressure drop of sandwich packings (above) derived based on pressure drop of conventional packings (below)

Due to the complexity of the prevailing physical phenomena, a rigorous prediction of the flooding points is hardly possible; it is usually estimated with the aid of empirical or semi-empirical models. Most of the semi-empirical flooding point correlations published in literature are based on three main approaches, namely the channel model (Rocha et al., 1993), the particle model (Stichlmair et al., 1989) and a model of a suspended bed of droplets for describing the gas velocity at the loading limit (Maćkowiak, 2010). The Wallis plot (Wallis, 1969) is an approach to provide a flooding point correlation based on experimental data. The main goal of this work is to determine the loading limits of structured packings and sandwich packings with the Wallis approach.

2. Experimental data

In the present study, experimental pressure drop data obtained with the system air/water under ambient conditions were analysed to determine gas and liquid flow rates at the loading limit. The hydraulic experiments were performed with two different types of structured packings and several sandwich packings. The geometric parameters of the investigated structured packings are shown in Table 1. Pressure drop measurements of the Montz packings were done by Brinkmann et al. (2012) at Julius Montz GmbH. In their study, hydraulic tests were carried out in a 0.6m diameter column, while the specific surface area was varied. Additionally, experimental data published by Spiegel and Meier (1994) was used. They considered the Influence of the specific surface area and the inclination of the flow channels on the flooding behaviour.

Table 1: Geometrical data for the structured packings studied

Packing	Column diameter d_c [mm]	Specific surface a_{geo} [m²/m³]	Declination angle α [°]
B1-250	DN600	250	45
B1-500	DN600	500	45
B1-750	DN600	750	45
Mellapak 125-X	DN1000	125	30
Mellapak 250-X	DN1000	250	30
Mellapak 250-Y	DN1000	250	45
Mellapak 500-Y	DN1000	500	45

Further, Brinkmann et al. (2012) investigated the pressure drop of sandwich packings. The latter are presented in Table 2. The investigations were carried out at BASF SE and at Julius Montz GmbH. In a previous study, Brinkmann et al. (2009) found that sandwich combinations containing the hold-up layer with a specific surface area of 750 m²/m³ showed the best hydraulic behaviour. All further hydraulic tests of sandwich packings were performed with this hold-up layer. Therefore, the influence of the specific surface area of this layer could be not considered. However, the specific surface area and the inclination of the flow channel in the de-entrainment layer were taken into account.

Table 2: Geometrical data for the sandwich packings studied

Packing combination	Column diameter d_c [mm]
B1-750T/B1-125	DN500
B1-750T/B1-150.60	DN500
B1-750T/B1-250M	DN500
B1-750T/B1-250M	DN1450

There exists a variety of methods to determine the loading limits of packed columns (Kister, 1992). One possibility is to read the gas load value at a fixed pressure drop and a constant liquid load from a pressure drop diagram. Rocha et al. (1993) observed the flooding point at a pressure drop of 10 mbar/m. Some studies showed much higher values resulting in the flooding region around 30 mbar/m. We assumed, according to Spiegel and Meier (1992) that flooding of structured packings occurs at 12 mbar/m.
For the determination of the loading limits of sandwich packings, the specific pressure drop profile can be used (see Figure 4). The profile is characterised by bending points that can be identified easily.

3. Flooding point correlation based on the Wallis plot

Initially, the Wallis plot (Wallis, 1969) was proposed to analyse the flooding condition for two phase countercurrent flow in vertical tubes, comprising annular liquid flow and vapour streaming upwards in the tube centre. Wallis (1969) suggested a linear relationship between the roots of the liquid and gas capacity factors. This was done for constant geometric conditions and material properties and for different fluid loads. McNulty and Hsieh (1982) applied the Wallis plot to determine the loading limits of columns containing structured packings and introduced, similar to Wallis (1969), the following equation,

$$\sqrt{C_G} = m\sqrt{C_L} + b \qquad (1)$$

where b and m are fitting parameters. The capacity factors in Eq(1) are defined as follows:

$$C_G = \frac{u_G}{\varepsilon} \frac{\sqrt{\rho_G}}{\sqrt{\rho_L - \rho_G}} \quad (2)$$

$$C_L = \frac{u_L}{\varepsilon} \frac{\sqrt{\rho_L}}{\sqrt{\rho_L - \rho_G}} \quad (3)$$

Many researchers (Spiegel and Meier, 1994) adapted the Wallis equation by using empirical hydrodynamics data for structured packings. Lockett et al. (2006) investigated rectification columns with structured packings and revealed the dependence of $b \sim a_{geo}^{-0.25}$, where a_{geo} is the specific surface area. Hanley (2012) considered the influence of material properties on flooding behaviour. Starting from a dimensional analysis, it could be shown that the fitting parameter b and m depend on the Bond number:

$$Bo = \frac{\rho_L (d_h)^2 g}{\sigma_L} \quad (4)$$

In the present work, the Wallis equation is used to predict the flooding point of structured packings as well as the loading limits of sandwich packings. For the estimation of the maximum gas load limit of structured packings, the specific surface area and the inclination of the flow channels are considered. As shown in Figure 4, the pressure drop profile of sandwich packings is characterised by the loading limits of both the hold-up layer and the de-entrainment layer. The flooding point of the hold-up layer can be derived based on the flooding limit of conventional packings. However, the maximum gas load of the de-entrainment layer is reduced as compared to conventional structured packings. Therefore, there is a need to estimate a new set of fitting parameters. From the analysis of the existing database, the following correlation was derived:

$$\sqrt{C_G} = m_1 Bo^{m_2} \sqrt{C_L} + b_1 \cos\alpha \, (g \, d_h)^{0.25} Bo^{b_2} \quad (5)$$

4. Simulation results

Parameters of Eq(5) were fitted to the experimentally determined loading limits of conventional and sandwich packings. This was done by the least square method, i.e. by varying the fitting parameters to minimise the sum of the squared deviations between simulated and experimental values (see Table 3).

Table 3: Obtained fitting parameters for Eq(5)

	m_1	m_2	b_1	b_2
Structured packings / Hold-up layer	1.004	-0.036	0.967	-0.044
Sanwich packings	3.396	-0.185	1.544	-0.127

The experimental data and the simulation results were plotted as a Wallis plot using Eq(5) (Figure 5). In Figure 5a, a comparison between the experiments and the simulation of Montz packings is shown. An analysis shows that b should depend on the specific surface area. In addition to the dependence of the specific surface area, the influence of the inclination angle of the flow channels on the loading limits (Figure 5b) can be reproduced by Eq(5). Figure 5c illustrates the relationship between the capacity factors at the flooding point of the hold-up layer and the sandwich packing B1-750T / B1-125.

Brinkmann et al. (2012) proposed a hydraulic model for sandwich packings. In this model, the prediction of pressure drop and capacity is based on the approach for the determination of fluid dynamics of packed columns suggested by Maćkowiak (2010). In Figure 5a, a Wallis plot for the hold-up layer (B1-750T) is shown. The model uses the flooding point correlation based on the “suspended bed of droplets” approach (Maćkowiak, 2010). The inaccuracy between simulated and experimental gas capacity factors grows with increasing liquid loads. As a result, the pressure drop values are underestimated before the flooding point and overestimated after the flooding point of the hold-up layer (Figure 5b).

A good agreement between the calculated and the measured pressure drop of sandwich packings can be achieved if the estimated flooding limit is accurate enough. Therefore, we implemented Eq(5) in the hydraulic model for sandwich packings by Brinkmann et al. (2012). Figure 6 shows the simulated and measured values of pressure drop versus the F-factor for different sandwich packings, with a good agreement between simulations and experiments.

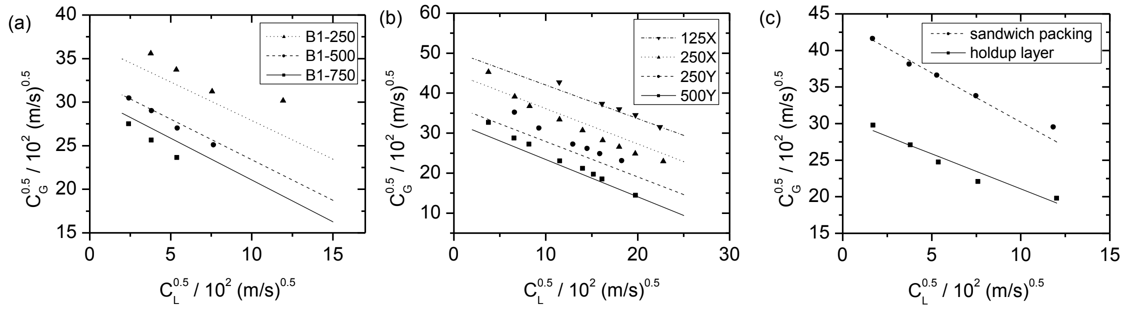

Figure 5: Wallis plot of Montz packings (a), Mellapak packings (b) and sandwich packings (c)

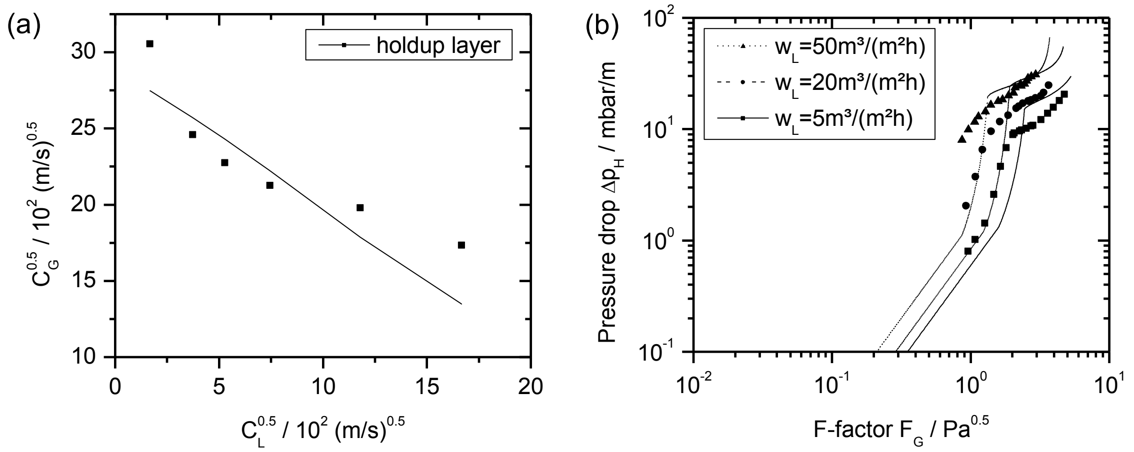

Figure 5: Comparison between simulated (lines) and experimental (points) values of capacity (hold-up layer B1-750T) (a) and pressure drop (B1-750T/B1-150.60) (b)

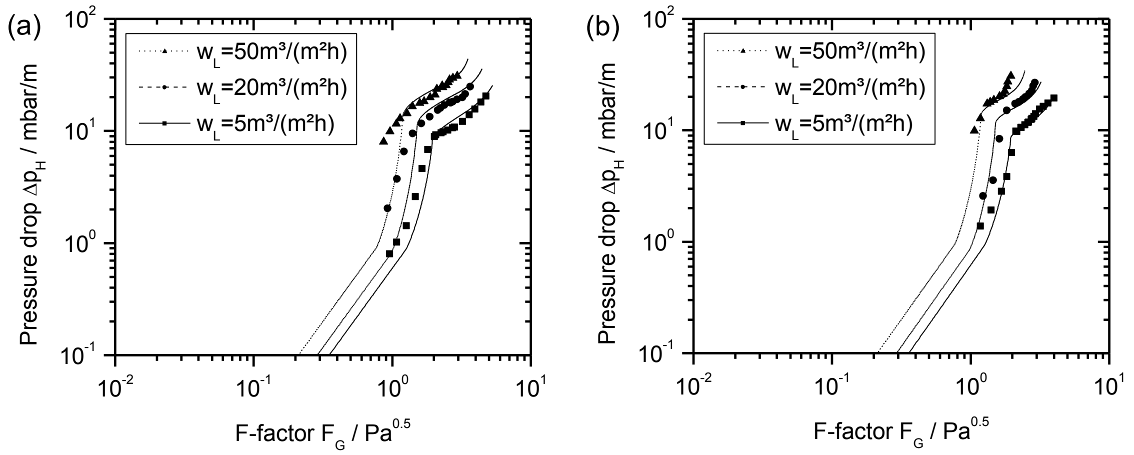

Figure 6: Comparison between simulated (lines) and experimental (points) pressure drop for B1-750T/B1-150.60 (a) and B1-750T/B1-250M (b)

5. Conclusions

In the present study, the hydraulic behaviour of columns containing structured packings was studied, particularly with regard to their flooding behaviour. The Wallis equation (Wallis, 1969) was used to predict flooding points based on available experimental data.

Experimental pressure drop data of structured packings and sandwich packings were analysed to estimate the loading limits. The gas velocities at flooding conditions of structured packings were read from pressure

drop profiles at 12 mbar/m and constant liquid load. For the determination of the sandwich packing loading limits, the pressure drop profile was used. The flooding limits of the hold-up layer as well as the flooding limits of the overall sandwich packing are represented by bending points in the pressure drop profile.
To predict the loading limits of conventional packings, the hold-up layer and the de-entrainment layer, two sets of fitting parameters are required. The influence of the specific surface area, the inclination angle and physical properties are considered in the adapted Wallis equation.
With the obtained correlation (Eq(5)), gas velocity under flooding conditions both in structured packings and in sandwich packings can be calculated. This correlation was implemented in the hydraulic model of sandwich packings (Brinkmann et al. 2012). In this way, the range of the applied model was extended and the predictivity improved.

Notation

Latin letters

a	specific surface, m²/m³
b	parameter Wallis equation, -
C	capacity factor, m/s
d	diameter, m
F	F-factor, $Pa^{0,5}$
g	gravitational constant, m/s²
h	hold-up, m³/m³
m	parameter Wallis equation, -
p	pressure, mbar
u	velocity, m/s
w	specific load, m³/(m²h)

Greek letters

α	declination angle, °
ε	void fraction, -
ρ	density, kg/m³
σ	surface tension, N/m

Subscripts

C	column
G	gas
h	hydraulic
H	height
L	liquid

Abbreviations

Bo	Bond number
DL	de-entrainment layer
FP	flooding point
HL	hold-up layer
LP	loading point

References

Brinkmann U., Hoffmann A., Kaibel B., Jödecke M., Kenig E.Y., 2009, A rate-based approach to calculate the performance of sandwich packings, Chemie Ingenieur Technik, 81, 1085 (in German).

Brinkmann U., Kaibel B., Jödecke M., Maćkowiak J., Kenig E.Y., 2012, Description of the fluid dynamics of sandwich packings, Chemie Ingenieur Technik, 84, 36-45 (in German).

Hanley B., 2012, On packed column hydraulics, AIChE Journal, 58, 1671-1682.

Jödecke M., Friese T., Schuch G., Kaibel B., Janzen H., 2006, Second generation sandwich packings – investigation results and applications, VDI-GVC Meeting Fluid Process Engineering, May, Würzburg, Germany (in German).

Kister H.Z., 1992, Distillation Design., McGraw-Hill, New York, United States.

Lockett M.J., Victor R.A., Billingham J.F., 2006, Structured packing flooding: its measurement and prediction, Distillation & Absorption, London, United Kingdom.

Maćkowiak J., 2010, Fluid dynamics of packed columns. Springer-Verlag, Berlin, Germany.

McNulty K.J., Hsieh C.L., 1982, Hydraulic performance and efficiency of koch Flexipac structured packings, AIChE Annual Meeting, December, Los Angeles, United States.

Metzen B., Shilkin A., Großmann C., 2010, Sandwich packings – investigation with an organic system at high liquid loads, ProcessNet Meeting Fluid Process Engineering, March, Fulda, Germany (in German).

Rocha J.A., Bravo J.L., Fair J.R., 1993, Distillation-columns containing structured packings – a comprehensive model for their performance. 1. Hydraulic models, Industrial & Engineering Chemistry Research, 32, 641-651.

Spiegel L., Meier W., 1994, Performance charakteristics of various types of Mellapak packings (productivity, pressuredifferntial, and defiency), Chemical and Petroleum Engineering, 30, 118-125.

Stichlmair J., Bravo J.L., Fair J.R., 1989, General model for prediction of pressure drop and capacity of countercurrent gas/liquid packed columns, Gas Separation & Purification, 3,19–28.

Wallis G.B., 1969, One-dimensional two-phase flow, McGraw-Hill, New York, USA.

Yazgi M., Kenig E.Y., 2013, Hydrodynamic-analogy-based modelling of CO_2 capture by aqueous monoethanolamine, Chemical Engineering Transactions, 35, 349-354.