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Experimental Investigation of Fluid Dynamics in Sandwich Packings with Ultrafast X-ray Tomography

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Sandwich packings consist of two layers of corrugated sheet structured packings with higher (holdup layer) and lower (de-entrainment layer) specific surface area alternatingly placed in the column. They are preferentially operated between the flooding points of both layers, which results in zones of bubbly flow, froth regime and liquid film flow in each sandwich element. Compared to conventional packed columns, sandwich packings can reach higher capacity and also higher separation efficiency as a result of intensive phase interactions. In the scope of a collaborative project, sandwich packings are experimentally and theoretically investigated. To provide detailed information on the heterogeneous flow patterns to derive reliable process models, ultrafast X-ray tomography is applied as a non-invasive measurement technique with high temporal and spatial resolution. In addition to local liquid holdup in the different layers of the packing, cross-sectional liquid distribution and axial transitions between the flow regimes are estimated. Furthermore, a method for the detection of the gas-liquid interfacial area is proposed.

1. Introduction

Structured packings have been a continuing subject of industrial design optimization. For further improvements, new concepts are necessary. The installation of sandwich packings (SP) in distillation and absorption columns is a promising approach to increase the separation efficiency of these processes that do not necessarily require very low pressure drop. These column internals are composed of two different layers of standard corrugated sheet structured packings, which are alternately arranged. The layer with higher specific surface area is called holdup layer (HL) while the other is called de-entrainment layer (DL). According to the concept of sandwich packings, the column is operated between the flooding points of both layers. This leads to axially inhomogeneous and highly dynamic flow patterns with higher gas-liquid interactions compared to the film flow in conventionally operated structured packings (Figure 1).

The idea to use different arrangements of standard packings was introduced and tested by Kaibel et al. (2000). Jödecke et al. (2006) showed an efficiency increase of 30 % with sandwich packings compared to conventional packed columns. Kashani et al. (2005) firstly analyzed the fluid dynamics of this novel packing arrangement and proposed a basic hydrodynamic model. Following this model concept, Brinkmann et al. (2012) developed different hydrodynamic correlations for each evolving flow regime, namely

- film flow in the de-entrainment layer,
- froth regime in the de-entrainment layer,
- bubble/ froth regime in the flooded holdup layer,

which are assumed to additively contribute according to their volumetric share in the total packing. This way, the total pressure drop (Δp^{SP}) of a sandwich packing is determined according to

$$\Delta p^{\mathrm{SP}} = \Delta p_{\mathrm{H}}^{\mathrm{HL}}\, n_{\mathrm{L}}^{\mathrm{HL}}\, H_{\mathrm{L}}^{\mathrm{HL}} + \Delta p_{\mathrm{H}}^{\mathrm{DL}}\, H_{\mathrm{L}}^{\mathrm{DL}} + \left(n_{\mathrm{L}}^{\mathrm{DL}} - 1\right)\left[\Delta p_{\mathrm{H}}^{\mathrm{DL}}\left(H_{\mathrm{L}}^{\mathrm{DL}} - H^{\mathrm{Froth}}\right) + \Delta p_{\mathrm{H}}^{\mathrm{Froth}}\, H^{\mathrm{Froth}}\right], \quad (1)$$

where Δp_{H} refers to the specific packing pressure drop and n_{L} is the number of layers with a height H_{L}.

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Yildirim et al. (2015) adapted the Wallis plot method to determine the loading limits of sandwich packings. Recently, Yildirim and Kenig (2015) utilized a rate-based model to simulate the separation behavior of distillation columns with such new internals. A comprehensive summary on the state of the art of sandwich packings can be found in Flechsig et al. (2016).

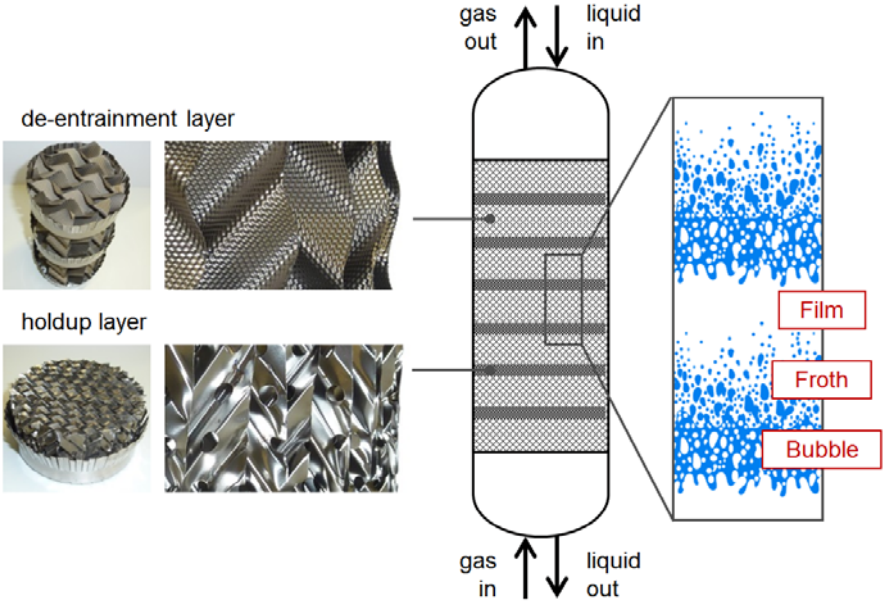

Figure 1: Arrangement of sandwich packings with characteristic flow patterns.

Currently, modeling still relies on a number of assumptions, especially regarding the liquid holdup of froth and bubbly sections, which are hardly accessible with conventional techniques. In particular, the froth regime height H^{Froth} is a relevant hydrodynamic parameter to estimate the volumetric share of each section within the packing (Eq 1). In addition, the interfacial area in these zones with intensive interactions between the gas and liquid phase, which are expected to cause the increased separation efficiency, is unknown.
We employed for the first time ultrafast X-ray tomography to get an insight into sandwich packings at very high temporal resolution to account for the flow dynamics. In this contribution, the experimental setup and the ultrafast X-ray tomography system are described. Furthermore, procedures for the parameter extraction are explained and initial results for radial and axial liquid holdup distribution as well as gas-liquid interfacial areas are shown.

2. Experimental setup

The experiments were carried out with seven de-entrainment and six holdup layers installed in a column with 100 mm inner diameter. Titanium packings (Julius Montz GmbH) were used to reduce their contribution to the X-ray attenuation. Packing types B1-500, B1-750 and B1-1000 were applied as holdup layers with different specific surface area a_{geo} and layer height. The types B1-250 and B1-250.60 were used as de-entrainment layers to investigate the influence of the corrugation angle α. Table 1 summarizes the combinations of packing layers studied in this work. Depending on the combination, the total packing height was 1.5 to 1.8 m.

Table 1: Sandwich packing configurations used in this study.

No.	$a_{\mathrm{geo,HL}}$ [1/m]	α_{HL} [°]	H_{HL} [mm]	$a_{\mathrm{geo,DL}}$ [1/m]	α_{DL} [°]	H_{DL} [mm]
1	750	45	50	250	45	196
2	750	45	30	250	45	196
3	750	45	70	250	45	196
4	500	45	50	250	45	196
5	1000	45	50	250	45	196
6	750	45	50	250	60	212

Deionized water and air were applied. To ensure constant and reproducible initial conditions, the air was saturated with water and the temperature was adjusted at 20 °C in the upstream bubble column. Liquid loads of 10, 20 and 50 m³/(m²h) and gas loads varied from $F_G = 0.5\ \mathrm{Pa}^{0.5}$ up to the packings flooding point were adjusted. The basic flow chart is shown in Figure 2a.

3. Ultrafast X-ray tomography

To account for the dynamic flow, the world-wide fastest, in-house developed X-ray computed tomography (CT) system was used. This non-invasive technique provides up to 8,000 cross-sectional images per second, which is much faster than medical CT systems. Instead of a mechanically moving source-detector arrangement, the rotating X-ray source is produced by rapidly sweeping a focused electron beam along a circular tungsten target. A concentric detector measures the intensity of the X-rays passing the column with the sandwich packing. The recorded raw data are reconstructed using the filtered back-projection algorithm, which results in a set of relative attenuation images. Typically, an image resolution of 256 x 256 pixels with 128 x 128 mm image size is chosen. Further details regarding the tomography system and the image reconstruction can be found elsewhere (Fischer et al., 2008; Fischer and Hampel, 2010; Janzen et al., 2013). The experimental setup including the ultrafast X-ray tomography installed at the column with sandwich packings can be seen in Figure 2b.

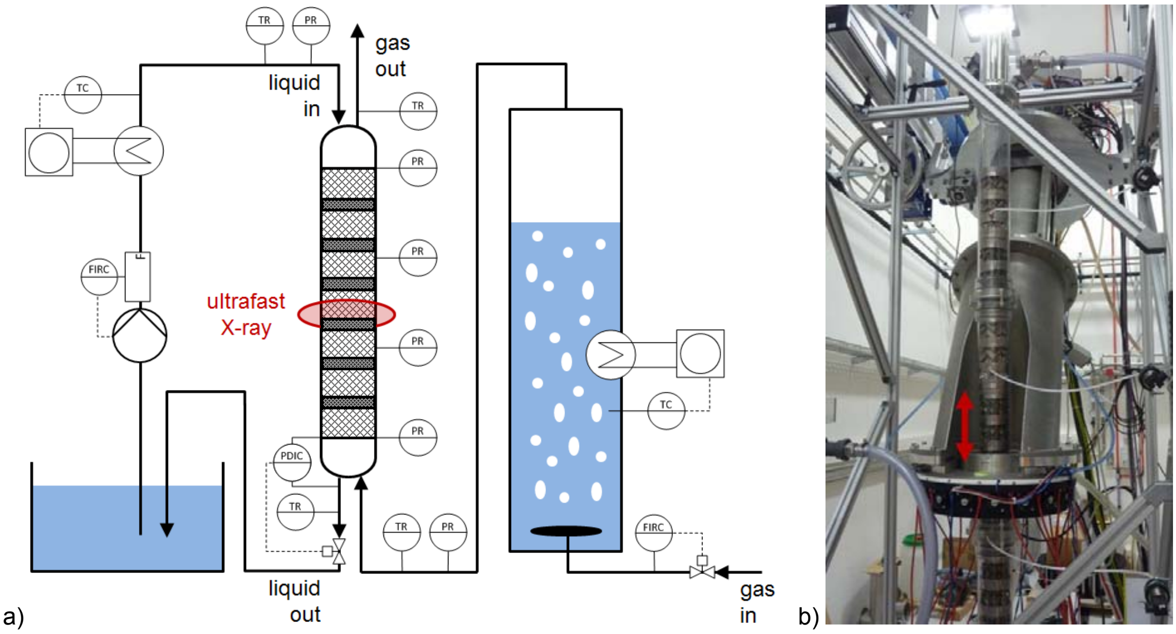

Figure 2: Basic flow chart of the test facility (a); column (Ø = 100 mm) with sandwich packings and ultrafast X-ray tomography system (b).

4. Parameter extraction

In this work, tomographic measurements with a frame rate of 1,000 images per second were performed. This results in a reasonable signal-to-noise ratio and a high structural resolution of about 1 mm. However, to extract liquid holdup and gas-liquid interfacial area from the reconstructed raw data, further image post-processing steps are required, which are described below.

4.1 Liquid holdup

To determine the liquid holdup in film, froth and bubbly regimes, the ultrafast X-ray tomography is applied at different heights along a sandwich packing. Besides the measurements at column operation, two reference measurements are needed. One is the so-called dry reference, which contains only the metal packing and air. The other includes the packing completely filled with liquid and is therefore named flooded reference. This way, the liquid holdup matrix $h_L(x, y)$ can be calculated by two-sided referencing according to

$$h_L(x,y) = \frac{\mu_{\mathrm{meas}}(x,y) - \mu_{\mathrm{dry}}(x,y)}{\mu_{\mathrm{flooded}}(x,y) - \mu_{\mathrm{dry}}(x,y)}, \qquad (2)$$

where μ is the local attenuation at position (x, y).

Figure 3 shows examples of the liquid holdup distribution for each characteristic flow pattern obtained from Eq (2).The applied measurement frequency of 1,000 Hz yields 10,000 images for a measurement duration of 10 s. The temporal behaviour of the cross-sectionally averaged liquid holdup values (red) are shown below together with the variation coefficients (blue) as a measure for the dynamics of the two-phase flow. The high variation coefficient for froth and bubbly flow indicate frequent local changes between gas and liquid and thus, high phase interactions, while low coefficients indicate stable film flow.

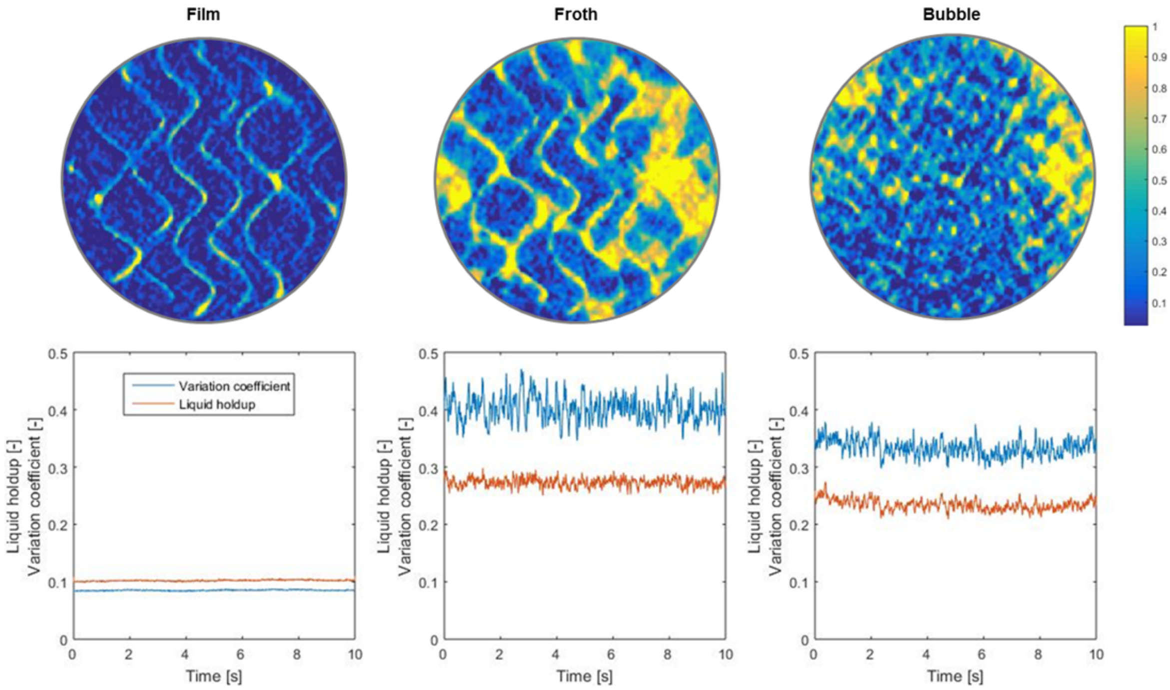

Figure 3: Liquid holdup distribution (upper row) and cross-sectionally averaged liquid holdup and variation coefficient for the corresponding measurement duration (lower row).

4.2 Froth regime height

As mentioned above, the froth regime height is an essential parameter within the additive hydrodynamic modeling approach. To detect the upper end of the froth regime, the CT system is vertically moved along the column during the scanning time (red arrow in Figure 2b) with a uniform speed of approx. 8 mm per second. These volumetric CT scans cover one holdup layer and one de-entrainment layer. The approximated holdup $h'_{\mathrm{L}}(x,y)$ is calculated based on a single-sided referencing according to

$$h'_{\mathrm{L}}(x,y) = 1.14\ \left(\mu_{\mathrm{meas}}(x,y) - \mu_{\mathrm{dry}}(x,y)\right), \tag{3}$$

with factor 1.14 considering the ratio between the absolute attenuation of water and the column wall (Zalucky et al., 2017).

Figure 4 shows the centre-line approximated liquid holdup along the sandwich packing. Similar to Figure 3, cross-sectionally averaged liquid holdup values and variation coefficients are also shown. The axial slope (expressed in terms of time), which is only accessible by ultrafast X-ray CT, reveals important information on the location and height of the individual flow patterns. The variation coefficient in the flooded holdup layer and the section of the froth regime is very high, indicating the very dynamic gas-liquid interactions. At the transition to film flow, the dynamics of the two-phase flow decrease steeply. The height of the froth regime can be determined at the intersection point between the piece-wisely fitted linear functions.

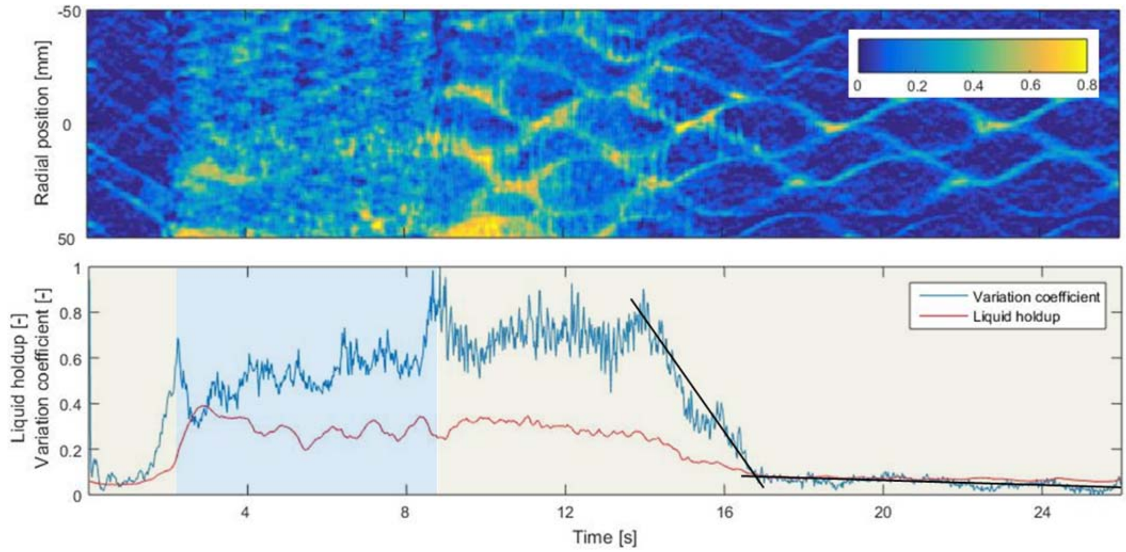

Figure 4: Approximated axial liquid holdup distribution in one sandwich (upper row) and corresponding average liquid holdup and variation coefficient (lower row).

4.3 Gas-liquid interfacial area

The interfacial area between gas and liquid is an important parameter for the mass transfer in separation processes and is thus crucial for modeling purpose. Due to the limited structural resolution of approx. 1 mm, an advanced method for the extraction of the gas-liquid interfacial area is required. Therefore, static phantoms for the three characteristic flow regimes in sandwich packings were manufactured mimicking the liquid phase with resin, which has similar X-ray attenuation characteristics as water (Figure 5a). The phantom was scanned with the ultrafast X-ray tomography as well as with micro computed tomography, which reveals the resin-air interphase with high resolution (approx. 70 µm). This is used to validate the parameter extraction methods applied to the ultrafast X-ray images.

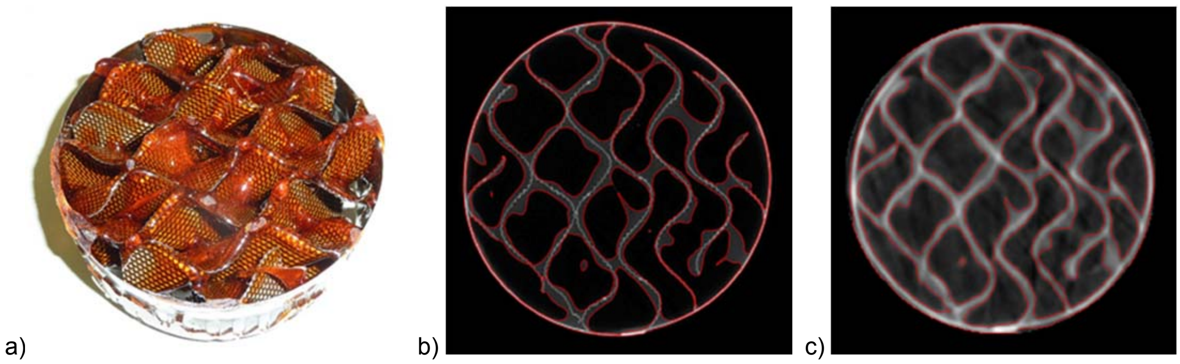

Figure 5: Static phantom of the froth regime with solid resin mimicking the liquid phase (a); cross-sectional image of the phantom obtained via micro-CT and highlighted phase boundaries (b); ultrafast X-ray CT cross-sectional image of the phantom with phase boundaries extracted via level-set segmentation (c).

The level-set segmentation according to Li et al. (2011) was applied to the CT data to extract the interfacial area. In Figures 5b and 5c, cross-sectional images from both CT systems are shown with the air-resin interfacial area detected by the level-set method with the standard deviation $\sigma = 3.5$.
Subsequently, the validated method was applied to the two-phase flow measurement data (Figure 6a). The interfacial area density, calculated frame by frame for a duration of 500 ms, is shown in Figure 6b.

a) b)

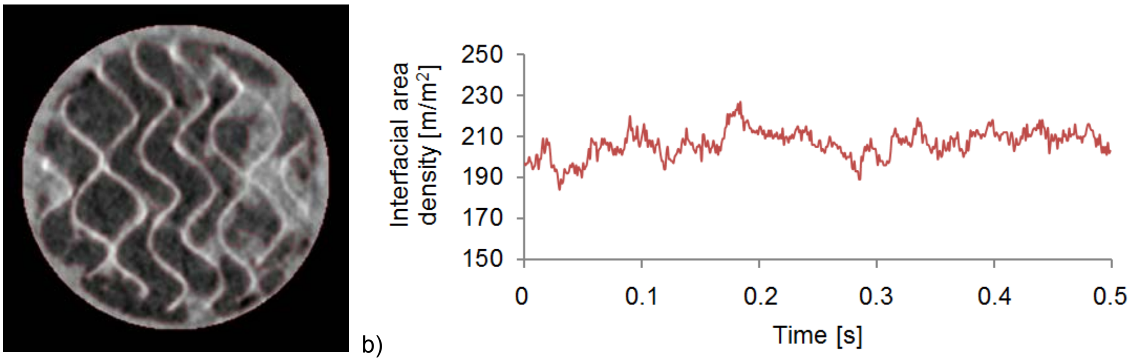

Figure 6: Level-set segmentation method for the detection of the gas-liquid interfacial area applied to ultrafast X-ray CT data from the froth regime (a); temporal behaviour of the interfacial area density in the froth regime (b).

5. Conclusions

To visualize the highly dynamic phase interactions in the froth and bubbly sections of sandwich packings, which can increase the overall separation efficiency, the ultrafast X-ray computed tomography was utilized. Proper image post-processing methods to extract liquid holdup, gas-liquid interfacial area and height of the respective sections were developed and validated with phantom data. These approaches will be applied for experimental data to derive correlations for their implementation in an additive separation model approach for reliable design of optimized sandwich packing configurations in the future.

Acknowledgments

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References

Brinkmann, U., Kaibel, B., Jödecke, M., Maćkowiak, J., Kenig, E.Y., 2012. Beschreibung der Fluiddynamik von Anstaupackungen. Chemie Ingenieur Technik 84, 36–45.

Fischer, F., Hampel, U., 2010. Ultra fast electron beam X-ray computed tomography for two-phase flow measurement. Nuclear Engineering and Design 240, 2254–2259.

Fischer, F., Hoppe, D., Schleicher, E., Mattausch, G., Flaske, H., Bartel, R., Hampel, U., 2008. An ultra fast electron beam x-ray tomography scanner. Measurement Science and Technology 19, 9.

Flechsig, S., Yildirim, Ö., Kenig, E.Y., 2016. Sandwich packings: State of the art. ChemBioEng Reviews 3, 174–185.

Janzen, A., Schubert, M., Barthel, F., Hampel, U., Kenig, E.Y., 2013. Investigation of dynamic liquid distribution and hold-up in structured packings using ultrafast electron beam X-ray tomography. Chemical Engineering and Processing: Process Intensification 66, 20–26.

Jödecke, M., Friese, T., Schuch, G., Kaibel, B., Jansen, H., 2006. The Sandwich Packing - A New Type of Structured Packing to Increase Capacity and Mass Transfer of Distillation Columns, in: Institution Chemical Engineers Symposium Series. Institution of Chemical Engineers, p. 786-789.

Kaibel, B., Kaibel, G., Stammer, A., Stroezel, M., Kind, M., 2000. Leistungssteigerung von Kolonnenpackungen durch Kombination von konventionellen Packungselementen. Chemie Ingenieur Technik 72, 962–963.

Kashani, N., Siegert, M., Sirch, T., 2005. A new kind of column packing for conventional and reactive distillation – the sandwich packing. Chemical Engineering & Technology 28, 549–552.

Li, C., Huang, R., Ding, Z., Gatenby, J.C., Metaxas, D.N., Gore, J.C., 2011. A level set method for image segmentation in the presence of intensity inhomogeneities with application to MRI. IEEE Transactions on Image Processing 20, 2007–2016.

Yildirim, Ö., Flechsig, S., Brinkmann, U., Kenig, E.Y., 2015. Application of the Wallis determination of the loading limits of structures packings and sandwich packings. Chemical Engineering Transactions 45, 1165–1170.

Yildirim, Ö., Kenig, E.Y., 2015. Rate-based modelling and simulation of distillation columns with sandwich packings. Chemical Engineering and Processing: Process Intensification 98, 147–154.

Zalucky, J., Wagner, M., Schubert, M., Lange, R., Hampel, U., 2017. Hydrodynamics of descending gas-liquid flows in solid foams: Liquid holdup, multiphase pressure drop and radial dispersion. Chemical Engineering Science 168, 480–494.