CHEMICAL ENGINEERING TRANSACTIONS
VOL. 69, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Elisabetta Brunazzi, Eva Sorensen

ISBN 978-88-95608-66-2; **ISSN** 2283-9216

Extended Performance Comparison of Different Pressure Drop, Hold-Up and Flooding Point Correlations for Packed Columns

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Hydraulic characteristics such as pressure drop, fractional liquid hold-up and flooding point are of significant design importance in describing random and/or structured packing performance. For this reason, accurate modelling of these parameters over a wide operating and physical property range has to be ensured. In the past, various research groups developed many correlations. The significant combined databases of the Separation Research Program (SRP) at the University of Texas and the Montanuniversitaet Leoben (MUL) provide the perfect basis to evaluate available correlations. The databases include pressure drop, hold-up and flooding point data for 50 different random (2nd, 3rd and 4th generation) and structured packings (sheet and grid structured packings) for different test systems under absorption and distillation conditions.
Eight correlations (Billet and Schultes 1991 and 1999, Wolf 2014, Engel 1999, SRP 1997, Delft 1997, Verschoof 1999, Maćkowiak 2003, Stichlmair 1989) were evaluated in an initial analysis. The best predictions were achieved with the model of Wolf 2014 and a modified model of Maćkowiak 2003 by Wolf-Zoellner.
The objective of this work is to use the large database and extend the performance investigation to further well-known correlations available in literature (Spiegel and Maier 1992, Brunazzi 2002, Bozzano 2007, NNA-Model of Piché 2001, GPDC of Kister 2007, Robbins 1991, Jammula 2014). Based on this evaluation, the performance of the various correlations is compared and the application fields of the various models are revealed. In particular, the work shows the operating ranges as well as packing types for which the models provide reliable results but also the weaknesses of the various correlations.

1. Introduction

The reliable prediction of hydraulic properties (pressure drop, flooding point and hold-up) is essential for the accurate design of packed columns. The pressure loss is not only important for the accurate design of the column but also for the blower sizing. Furthermore in distillation, the pressure loss affects the pressure at the bottom of the column and thus the temperature in the column sump which is especially important if thermally sensitive mixtures should be separated. The flooding point defines the maximum load of counter current operated columns. An accurate prediction of the flooding point is essential for the column diameter determination and to prevent an over or under design. The fractional liquid hold-up prediction allows the determination of the liquid mean residence time in the packing and is in particular important when distilling temperature sensitive mixtures or in reactive absorption processes.
In the last few decades, many hydraulic models have been published by different research groups. The appropriate selection of the models can be very challenging. Some authors (Kister 1992, Engel 1999, Grabbert and Bonitz 1998, Tsai 2010) have compared a few different models but many of the available models were not included. The aim of this work is to use the large hydraulic database obtained at the experimental absorption plants of the Chair of Process Engineering at the Montanuniversitaet Leoben (MUL) and of the Separation Research Program (SRP) at the University of Texas (SRP) as well as of the SRP distillation column to examine the already published hydraulic models. Wolf-Zoellner et al. 2018 evaluated eight correlations (Billet und Schultes 1991, 1999; Wolf 2014, Engel 1999, Stichlmair et al. 1989, Maćkowiak

2003, Olujić 1997 (=Delft-Model 1997), Gualito et al. 1997 (=SRP-Model 1997)). In this paper, the performance comparison is extended to the following models: Spiegel and Meier 1992, Suess and Spiegel 1992, Brunazzi et al. 2002, Bozzano et al. 2007, Kister et al. 2007, Robbins 1991, Jammula 2014, Piché et al. 2001a and 2001b.

2. Experimental systems

Both institutions, SRP and MUL, use similar measurement columns with an inner diameter of about 420 mm to perform the packing tests for absorption. The detailed description of the experimental set-up at MUL can be found in Wolf et al. 2015 and of SRP in Song 2017. Comparative results obtained as well as the examined operating range has been addressed in Wolf-Zoellner et al. 2018. An experimental SRP distillation dataset with the cyclohexane/n-heptane (C6/C7) system was added for this evaluation. The experiments were conducted using a 428 mm column at pressures of 0.165 bar, 0.333 bar, 1.655 bar and 4.137 bar and a detailed description of the set-up and the operating conditions can be found in Olujić et al. 2000.

3. Correlations for hydraulic modelling

The models of Robbins and Kister were developed for random and structured packings. The NNA-model of Piché et al. was solely developed for random packings and the models of Brunazzi, Bozzano, Spiegel and Meier, Suess and Spiegel and Jammula are only applied to structured packings. The appropriate model applications are shown in Table 1.

Table 1: Application fields of the examined correlations for hydraulic modelling

Model	Random packing	Structured packing	Pressure loss	Hold-up	Flooding point
Brunazzi	-	yes	yes	yes	wallis-plot
Bozzano	-	yes	yes	yes	yes
GPDC - Kister	yes	yes	yes	-	yes
Robbins	yes	yes	yes	-	-
Spiegel and Meier	-	yes	yes	-	wallis-plot
Suess and Spiegel	-	yes	-	yes	-
Jammula	-	yes	-	yes	yes
NNA-Model of Piché	yes	-	yes	yes	-

Based on the assumptions of a falling film Brunazzi and Paglianti 1997 developed a mechanistic pressure drop model, which includes the contributions of frictional, gravitational and acceleration losses. The model was validated for five types of structured packings for which four empirical constants are given in Brunazzi and Paglianti 1997. Two empirical constants can be derived from the dry pressure drop results and the two others are used to fit the irrigated pressure drop. Unfortunately, the detailed description in determining these empirical constants is missing in the paper. The model requires the preloading liquid hold-up as input variable. Therefore, a second model is necessary to determine the liquid hold-up. In the present evaluation of the Brunazzi-model, the preloading hold-up was calculated using the modified model of Maćkowiak which performed most reliable in Wolf-Zoellner et al. 2018.

Bozzano et al. 2007 developed a completely theoretical model for the calculation of pressure drop, hold-up, loading and flooding point for structured packings that does not need any packing empirical constants. Unfortunately, documentation of the model is not described sufficiently enough as the required variables are not defined. Therefore, calculation based on the given equations is not possible.

The generalized pressure drop correlation (GPDC) charts have been developed by Sherwood and Eckert and continuously improved by different researchers over the years. The latest chart for random packings was developed by Strigle 1994 and the latest version for structured packings is given in Kister et al. 2007. As it is impractical to evaluate such a large database by reading each pressure drop value off a diagram, the graphical version was converted into an equation. Tsai 2010 found an existing equation in Aspen Plus (software developed by Aspen Tech). Its generic form is shown in Equation (1). As the Aspen software only included constants for an older version of the chart, Tsai updated the constants in a way that the equation is able to fit the chart given in Kister et al. 2007. To calculate the pressure drop for random packings as well the constants for the random packing chart were derived in this work and are given together with the constants for structured packings in Table 2. (CP =capacity parameter, F_{lv} = flow parameter, $\Delta P/H$ = pressure loss)

$$CP = \frac{C_1 * \left(\frac{\Delta P}{H}\right)^{C_2} * \left[1 - exp\left(C_6 * F_{lv}^{C_7}\right)\right]}{\left[1 + C_3 * \left(\frac{\Delta P}{H}\right)^{\left(C_2/C_4\right)} * F_{lv}^{C_5}\right]^{C_4}} \tag{1}$$

Table 2: Constants for numerical version of GPDC

GPDC type	C_1	C_2	C_3	C_4	C_5	C_6	C_7
structured packings [in H_2O/ft]	3.8617	0.6609	6.3763	0.7206	0.2898	-0.9093	-0.6819
random packings [in H_2O/ft]	2.7561	0.5778	5.3597	0.5545	0.4046	-1.4234	-0.6022

In 1991, Robbins developed a relatively simple correlation for the pressure loss prediction based on the equations developed by Leva 1954 as an alternative to the generalized pressure drop correlation (GPDC) charts. The equations are simple as no iteration is necessary and the only necessary empirical constant is called packing factor and can be calculated based on the dry pressure drop results of a packing. The model uses imperial units instead of SI units so the user has to be careful.

The research group of Piché, Larachi and Grandjean developed a fluid dynamic model based on a neuronal network analysis. Therefore, they defined 20 dimensionless quantities that were used as basis for the neural network and based on those they tried hundreds of different compositions of the quantities for the best results. The model is complex and their group provides an online spreadsheet to calculate the hydraulic properties. Furthermore, the spreadsheet includes the packing properties for a huge amount of packings as well as the additionally required packing sphericity. (www.gch.ulaval.ca/flarachi/)

Spiegel and Meier 1992 developed a model for the prediction of pressure drop and flooding point for four different structured packings. They divided the pressure drop calculation into a preloading and a loading region where the pressure drop calculation in the loading region needs the flooding point. The flooding point can be derived by using the given Wallis diagram. In this chart only values for the four Mellapak packings Mellapak 125X, 250X, 250Y and 500Y are depicted and therefore the model performance can just be evaluated for these packings.

Suess and Spiegel 1992 developed a liquid hold-up correlation for the preloading region for structured packings that is only dependent on the liquid load, the liquid viscosity and the geometrical surface area.

Jammula developed a correlation for liquid hold-up and flooding point for structured packings that does not need any empirical parameter. The liquid hold-up correlation is based on a modified model for the liquid film thickness and the correlation for the flooding point gas velocity on the Wallis equation.

4. Modelling results

4.1 Pressure drop modelling results

In general, the examined pressure drop correlations predict the packing pressure drop reasonably well as shown in Tables 3 and 4. The Robbins correlation shows large deviations for all packings that have a packing factor F_P smaller than 7. The reason for this behavior needs further investigation. The Kister GPDC correlation shows reliable results for all examined structured packings but for the random packings RSR #0.3, RSR #0.5 and RMSR 25-3, the model predicts too high pressure drops in the loading region which leads also to greater mean deviations. The NNA model of Piché et al. predicts the pressure drop for most of the examined packings within a mean deviation of 50% but for some, it even leads to mean deviations of more than 100%. Therefore, this model should be used with caution. The Spiegel and Meier model provides reliable predictions for the packings it was developed for but the required use of the Wallis plot is impractical. Good pressure drop predictions can be achieved with the Brunazzi model, although it needs four empirical constants. Nevertheless, it is unable to predict distillation pressure drop at higher operating pressures as the evaluation at 1.6 and 4.1 bar shows.

4.2 Liquid hold-up modelling results

The herein examined models (Tables 5 and 6) are not able to reliably predict the liquid hold-up as for example, the modified Maćkowiak model or the Billet and Schultes model in Wolf-Zoellner et al. 2018 do. Nevertheless, it is interesting that with the simple equation for the preloading region of Suess and Spiegel, originally developed for structured packings, promising results for structured as well as random packings can be achieved. The Brunazzi model in combination with the Maćkowiak model for the preloading hold-up achieves very good agreement except for systems with a high liquid viscosity (14 mPa*s through adding polyethylene oxide to water). The huge advantage of the Jammula model is that it does not need any empirical constants but the results are unsatisfactory.

Table 3: Mean deviation of pressure loss [%] – Air/water system – random packings (M=Metal, P=Plastic)*

Packing	Material*	Robbins	Kister GPDC	NNA-Model Piché
CMR 2	M	24	39	38
CMR 2A	P	9	15	38
IMTP 40	M	11	35	47
1 in Pall Ring	M	16	44	49
1 in Pall Ring	P	29	45	18
2 in Pall Ring	M	7	18	21
RSR #0.3	M	15	49	33
RSR #0.5	M	18	30	26
RSR #0.7	M	19	15	146
Hiflow 50-0	P	37	22	120
Hiflow 50-6	P	96	28	149
Raflux 25-5	M	18	34	19
Raflux 50-5	M	14	29	18
RMSR 25-3	M	11	61	37
RMSR 50-4	M	15	24	110
RMSR 70-5	M	106	23	54

Table 4: Mean deviation of pressure loss [%] – Air/water system – structured packings (M=Metal, P=Plastic)*

Packing	Material*	Robbins	Kister GPDC	Brunazzi (+ Maćkowiak)	Spiegel and Meier
Mellagrid 64Y	M	101	21	27	-
Mellapak 125Y	M	27	30	23	-
Mellapak 200Y	M	21	26	17	-
Mellapak 200X Plus	M	74	25	38	-
Mellapak 250X	M	36	25	23	20
Mellapak 250X high viscosity (14mPa*s)	M	36	30	36	28
Mellapak 250Y	M	17	24	20	20
RMP N 250Y organic/distillation	M	18	34	125	22
Mellapak 250Y smooth	M	23	26	16	21
Mellapak 252Y	M	19	17	17	-
Mellapak 252Y high viscosity (14mPa*s)	M	19	30	23	-
GTC 350Y	M	36	28	38	-
RMP S 350Y	M	18	28	16	-
Mellapak 500Y	M	37	25	17	34
RSP 200	M	19	24	-	-
RSP 250	M	17	20	-	-
RSP 300	M	20	16	-	-
Hiflow Plus #1	P	20	19	-	-
Hiflow Plus #2	P	130	22	-	-

4.3 Flooding point modelling results

Flooding points can be calculated with the Kister GPDC-model for random and structured packings and with the Jammula-model for structured packings. The Jammula calculation does not need any empirical packing constant and predicts all available flooding points for sheet structured packings within a mean deviation of 22%. Based on the Kister correlation, the flooding points for random packings can be predicted within a mean deviation of 17,5% and for structured packings within a mean deviation of 12%.

Table 5: Mean deviation of hold-up [%] – Air/water system – random packings (M=Metal, P=Plastic)*

Packing	Material*	Suess und Spiegel	NNA-Model Piché
1 in Pall Ring	P	28	36
RSR #0.3	M	36	75
RSR #0.5	M	47	16
RSR #0.7	M	23	103
Hiflow 50-0	P	51	48
Hiflow 50-6	P	48	40
Raflux 25-5	M	43	15
Raflux 50-5	M	37	56
RMSR 50-4	M	36	62
RMSR 70-5	M	43	182

Table 6: Mean deviation of hold-up [%] – Air/water system – structured packings (M=Metal, P=Plastic)*

Packing	Material*	Brunazzi (+ Maćkowiak)	Suess and Spiegel	Jammula
Mellagrid 64Y	M	30	43	39
Mellapak 125Y	M	41	70	35
Mellapak 200Y	M	21	40	30
Mellapak 200X Plus	M	10	28	17
Mellapak 250X	M	25	46	61
Mellapak 250X high viscosity (14mPa*s)	M	62	62	77
Mellapak 250Y	M	17	20	27
Mellapak 250Y smooth	M	25	22	41
Mellapak 252Y	M	21	45	59
Mellapak 252Y high viscosity (14mPa*s)	M	72	60	109
GTC 350Y	M	12	14	16
RSP 200	M	-	30	-
RSP 250	M	-	39	-
Hiflow Plus #1	P	-	19	-
Hiflow Plus #2	P	-	30	-

5. Conclusion

Combining the results of the current work and the performance comparison in Wolf-Zoellner et al. 2018, the modified Maćkowiak-model is highly recommended for fluid dynamic calculations due to its overall good data agreement for random and structured packings for pressure drop, hold-up and flooding point prediction and the need of just one empirical constant. For pressure drop and flooding point estimates, the Kister GPDC-chart is also a good alternative as it is simple and clear in its use, besides its good data agreement.

6. Outlook

Six correlations have been examined within this paper and eight correlations in Wolf-Zoellner et al. 2018 but there are still further hydraulic correlations in the literature (e.g. Mersmann 1994, Grabbert and Bonitz 1998) that also should be examined concerning their modelling performance. Furthermore, the available database should be continuously extended. In particular, it should include a larger variety of test systems. The end result of this research should be exact recommendations on which model should be used for which packing type and under which conditions. Therefore, the exact limitations of all models should be examined and compared with each other.

Acknowledgments

The author would like to thank the Separations Research Program (SRP) Staff for their great support and the possibility to work with their large pressure drop and hold-up database as well as for the great hospitality during my six months stay at SRP.

References

Billet R., Schultes M., 1991, Modelling of pressure drop in packed columns, Chemical Engineering & Technology, 14 (2), 89–95.

Billet R., Schultes M., 1999, Prediction of mass transfer columns with dumped and arranged packings, Chemical Engineering Research and Design, 77 (6), 498–504.

Bozzano G., Dente M., Corna P., 2007, A phenomenological model for fluid-dynamics evaluation of structured packing systems, AIDIC Chemical engineering transactions, Vol. 12, 189–194.

Brunazzi E., Paglianti A., 1997, Mechanistic pressure drop model for columns containing structured packings, AIChE J., 43 (2), 317–327.

Brunazzi E., Paglianti A., Spiegel L., Tolaini F., 2002, Hydrodynamics of a gas-liquid column equipped with MellapakPlus packing. IChemE (Hg.): Proceedings of the International Conference on Distillation and Absorption, Baden-Baden, Germany.

Engel V., 1999, Fluiddynamik in Packungskolonnen für Gas-Flüssig-Systeme, PhD Thesis, TU Munich, Lehrstuhl für Fluidverfahrenstechnik, Munich, Germany. (in German)

Grabbert G., Bonitz R., 1998, Fluiddynamik bei der Zweiphasenströmung durch Füllkörper- und Packungskolonnen, Freiberger Forschungshefte, TU Bergakademie, Freiberg, Germany. (in German)

Gualito J. J., Cerino F. J., Cardenas J. C., Rocha J. A., 1997, Design method for distillation columns filled with metallic, ceramic, or plastic structured packings, Ind. Eng. Chem. Res., 36 (5), 1747–1757.

Jammula A. K., 2014, New liquid holdup, load point and flooding velocity models in different regions of operations for a structured packed column, PhD Thesis, Oklahoma State University, Oklahoma, USA.

Kister H. Z., 1992, Distillation design, McGraw Hill, New York, USA.

Kister H. Z., Scherffius, J., Afshar, K., Abkar, E., 2007, Realistically predict capacity and pressure drop for packed columns, Chemical Engineering Progress, 103 (7), 28–38.

Leva M., 1954, Flow through irrigated dumped packings, Chem. Eng. Progress Symp. Ser., 50, 51-56.

Maćkowiak J., 2003, Fluiddynamik von Füllkörpern und Packungen, Grundlagen der Kolonnenauslegung, Springer, Berlin, Germany. (in German)

Mersmann A, 1994, Druckverlust und Flutpunkt in berieselten Packungen, VDI-Wärmeatlas, 7. Edition, VDI-Verlag, Germany. (in German)

Olujić Ž., 1997, Development of a complete simulation model for predicting the hydraulic and separation performance of distillation columns equipped with structured packings, Chemical and Biochemical Engineering Quarterly 11 (1), 31–46.

Olujić Ž., Seibert A.F, Fair J.R, 2000, Influence of corrugation geometry on the performance of structured packings: an experimental study, Chemical Engineering and Processing: Process Intensification 39 (4), 335–342.

Piché S., Larachi F., Grandjean B.P.A., 2001a, Improved liquid hold-up correlation for randomly packed towers, Chemical Engineering Research and Design, 79 (1), 71–80.

Piché S. R., Larachi F., Grandjean B. P. A., 2001b, Improving the prediction of irrigated pressure drop in packed absorption towers, Can. J. Chem. Eng., 79 (4), 584–594.

Robbins L. A., 1991, Improve pressure-drop prediction with a new correlation, Chemical Engineering Progress, 87, 87–91.

Song D., 2017, Effect of Liquid Viscosity on Liquid Film Mass Transfer for Packings, PhD Thesis, University of Texas at Austin, Austin, USA.

Spiegel L., Meier W., 1992, A generalized pressure drop model for structured packings, IChemE (Hg.): Distillation and Absorption, B85-B94, Birmingham, UK.

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 (1), 19–28.

Strigle R. F., 1994, Packed tower design and applications. Random and structured packings, Gulf Pub. Co., Houston, USA.

Suess P., Spiegel L., 1992, Hold-up of mellapak structured packings, Chemical Engineering and Processing: Process Intensification, 31 (2), 119–124.

Tsai R. E., 2010, Mass Transfer Area of Structured Packing, PhD Thesis, University of Texas at Austin, Austin, USA.

Wolf V., Lehner M., Hoffmann K., 2015, Modification of the Billet and Schultes-Model for the hydraulic modelling of random and structured packing, AIChE Spring Meeting, 144, Austin, USA.

Wolf V., 2014, Entwicklung eines hydraulischen Modells für eine neuartige Gitterstrukturpackung, PhD Thesis, Montanuniversitaet Leoben, Chair of Process Engineering, Leoben, Austria. (in German)

Wolf-Zoellner V., Seibert F., Lehner M., 2018, Performance comparison of different pressure drop, hold-up and flooding point correlations for packed columns, Chem. Eng. Res. Des. (under review).