

Hydraulic Investigations of the Operating Limits of High Performance Trays

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Abstract. In the course of a more fluctuating power supply due to renewable energy sources, the need for tray columns with flexible operability increases. Accordingly, further research is required to better predict the behavior at load limits – especially for fixed and float valve trays. Within this work, the hydraulic behavior of numerous valve tray configurations is investigated employing a 1.2 m diameter gas/liquid (air/water) column test rig. Its performance has been validated on the base of sieve trays, which have already been extensively studied in the literature. In order to obtain significant results, the weeping and entrainment limits in particular, as well as froth height and pressure drop, are measured quantitatively in the experiments. By varying the geometry parameters, numerous different cases can be investigated. Based on all the data obtained, reliable statements can be made about the validity and applicability of calculation models known from the literature.

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1. Introduction

One of the biggest issues of our time is the quest for a more sustainable energy supply, which is pursued through an energy transition towards more renewable energy sources. This leads to a strongly fluctuating power availability in the electricity supply of big companies, to which the plant operators must react with a flexible operation of their plants. As a consequence, a precise knowledge of the operating behavior at their load limits is required. In thermal separation technology, the behavior of the widely used tray columns must be considered in this context. Starting from the classical sieve trays, today also fixed and float valve trays are mainly used in industrial applications. This is why they are constantly being further developed and optimized, so that nowadays new forms of high performance valve trays are being pushed frequently. Although valve trays are generally considered as well researched, the details of their operating limits are not generally available – especially of those with push valves.

For this reason, the IGF research project “Tools and methods for improved hydraulic design of cross-flow trays with high performance valves” is concerned with the detailed investigation of the hydraulic behavior of valve trays. As part of this project, a gas/liquid column test rig (air/water) with a diameter of 1.2 m was set up at the Institute of Plant and Process Technology at the Technical University of Munich. To validate the performance of the test rig, measurements were carried out with well-studied sieve trays and evaluated with model approaches from the literature. After that, the test rig is used to investigate numerous valve tray configurations, selected with regard to all relevant valve types used in the industry. This work presents initial findings based on the investigation of sieve, float and fixed valve trays.

2. Theoretical basics

For a complete hydraulic column design, numerous parameters are required [1]. At first, there is the pressure drop, which is subject to numerous studies published in the literature. Especially with regard to sieve trays, many authors have developed models on dry and total pressure drop [2,3]. For float valve trays, there are also some specific publications dealing with pressure drop correlations [4,5]. Furthermore, some suppliers of float valve trays have published design manuals, which provide valuable models for the calculation of these trays [6-8]. As fixed valves are a relatively new type of tray element, the availability of models is considerably lower for this type. It is therefore necessary to adapt existing models of sieve and float valve trays in order to apply them to fixed valve trays.

Another meaningful value of hydraulic column design is the froth height on the tray. It can be used as a criterion for the quality of mass transfer, as the froth height can be related to the available mass transfer area. In the literature, there are numerous models that can be used for the calculation of the froth height on sieve trays. A distinction can be made between models that refer directly to the value of the froth height [2,3,9], or combinations that can be made with models of the clear liquid height on the tray [10] with an aeration factor model of another author. For float and fixed

valve trays, adaptations to the correlations of sieve trays have to be made as there is still little research available. The adaptations carried out in this work are based on an equivalent hydraulic diameter for a corresponding sieve tray configuration. This equivalent diameter is derived for the curtain area of the valve, given an equivalent relative free area and number of openings, resulting in an equivalent area of the corresponding openings.

For the investigation of weeping in tray columns, only few reliable correlations are published in the literature [11,12]. Especially for valve trays, there is still need for research on the weeping behavior, which is why also in this case sieve tray models have to be adapted on valve trays. An additional source for further models is the column design software TrayHeart® [13], which provides an unpublished weeping model especially for fixed valves.

In the case of entrainment studies, there are several publications that deal with the entrainment of sieve trays [2,14] or even bubble cap trays [15]. There are also models that were developed for the application on several tray types [16]. Nevertheless, for a comprehensive investigation of fixed valves again models of other tray types have to be adapted due to a sparse study availability.

3. Test rig for hydraulic investigations

The basic design of the column test rig consists of several transparent shell sections between which the column trays are flanged. For the trays, a modular concept with a separation of the active area and the tray base plate has been realized, so that the change between different valve configurations can be carried out easily. To capture the entrainment, a catch sieve tray equipped with a wire mesh demister is installed above the upper tray to collect the liquid carried upwards. Below the lower tray, a chimney tray is installed for the collection of spatially resolved weeping by the installation of separator plates. Furthermore, this tray serves to ensure a proper gas distribution on the lower tray. To prevent the influence of mass transfer in the column, the air is saturated before entering the column. As the aim of the test rig is the investigation of a wide range of different tray configurations, the construction is designed to be very flexible, so that not only the valve configuration, but also weir and clearance height can be changed easily. For the variation of the different valve parameters, numerous valve trays with different geometric parameters (valve density, valve shape, lift height, relative free area) have been chosen in cooperation with industry partners.

In order to define a suitable basic geometry for downcomer and active area, a detailed hydraulic investigation was made in which all hydraulic limits were considered. For this purpose, numerous design scenarios were created for a column diameter of $D = 1200$ mm and a tray spacing of $H = 500$ mm. On this basis, the geometric parameters listed in Table 1 were chosen. The limits of the operational data also given in Table 1 are due to the capacity of the existing fan and pump.

Table 1.

Geometric and operational data of the test rig configuration: Column diameter D , tray spacing H , number of trays N_{trays} , active area A_{ac} , weir length l_w , minimum and maximum F-factor (referring to active area) $F_{ac,min}$ and $F_{ac,max}$, minimum and maximum liquid load $\dot{V}_{L,min}$ and $\dot{V}_{L,max}$.

D	H	N_{trays}	A_{ac}	l_w	$F_{ac,min}$	$F_{ac,max}$	$\dot{V}_{L,min}$	$\dot{V}_{L,max}$
1.2 m	0.5 m	2	0.856 m ²	0.907 m	$0.8 \sqrt{\text{Pa}}$	$2.6 \sqrt{\text{Pa}}$	$5 \frac{\text{m}^3}{\text{h}}$	$40 \frac{\text{m}^3}{\text{h}}$

To ensure reliable and automated recording of the measured values, extensive measurement equipment is implemented in the test rig and the measured values are handled in a process control system. In addition to the recording of the volume flows of liquid and gas, numerous process parameters like air humidity, temperature and pressure drop are measured at several points of the test rig. For the evaluation of the collected data, all values are averaged over a time interval of $\Delta t = 20$ s.

A special feature of the test rig is the automatic measurement of the froth height with the measuring light curtain RapiDOScan® [17]. It consists of a transmitter and receiver unit facing each other on the outside of the column, ensuring non-invasive measurement. With a resolution of $\Delta s = 2.5$ mm and a measuring cycle time of $\Delta t = 0.96$ ms, the detector identifies the first beam that is not interrupted by the froth and therefore provides a reliable measurement method for the froth height on the tray. In Fig. 1, a tray of the test rig with the RapiDOScan® is shown before and during operation.

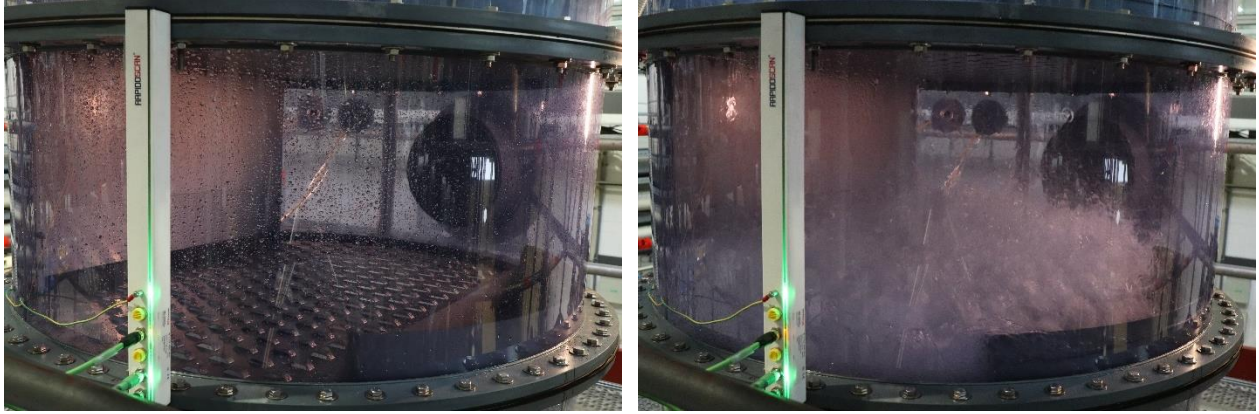


Fig. 1 Test rig with R-FV fixed valves before and during operation.

Within the scope of this work, three different tray configurations have been investigated at a weir height of $h_w = 50$ mm and a clearance height of $h_{cl} = 40$ mm. The geometrical data of the valve configurations is given in Table 2.

Table 2.

Geometrical data of the investigated tray configurations: relative free area φ , hole diameter d_h , valve lift height h_{lift} , number N_h of elements.

Tray type	φ	d_h	h_{lift}	N_h
Sieve	10 %	10 mm	-	1093
Float valve V1-1.5 (Raschig)	12 %	39 mm	8.1 mm	124
Fixed valve R-FV (Raschig)	10 %	-	7.0 mm	189

4. Results

In the course of a validation phase including numerous series of measurements, it could be confirmed that the system delivers reliable and repeatable measurement values. Based on the obtained results, comparisons with models published in the literature are carried out with regard to various parameters in the following. The presented models were selected considering the most common models used in industry. If not specifically mentioned in the following, the test rig geometry is in the valid range of the geometric ranges specified in the literature models. Furthermore, all models are intended for use with air/water systems and most of them have also been developed considering respective data.

4.1 Pressure drop

After studies on the pressure drop of sieve trays, which fitted to the established models very well, the pressure drop of float valve trays was investigated. The measured values and correlations are depicted in Fig. 2. As can be seen in the diagram of the dry pressure drop Δp_d (Fig. 2, left), the models differ significantly from each other. The open and closed balance point, that represents the point at which all valves are open respectively closed, is not included in the models of Norton [7] and Nutter [8], which leads to major deviations at gas loads beneath the open balance point. As the Nutter model is designed for the rectangular BDH valves, an adaptation to the V1 valves was made based on the equivalent hole diameter explained in section 2. The best fitting curve for the measured data provides the model of Glitsch [6] with an average absolute deviation of 10 % and a maximum deviation of 13 %. Considering the total pressure drop Δp_{tot} of the tray (Fig. 2, right), the chosen models show less deviations. The best fitting model in this case is the model of Norton [7] with an average absolute deviation of 3 %. For further comparison, a calculation was also carried out with different supplier software. As can be seen, the results do not provide a consistent image either.

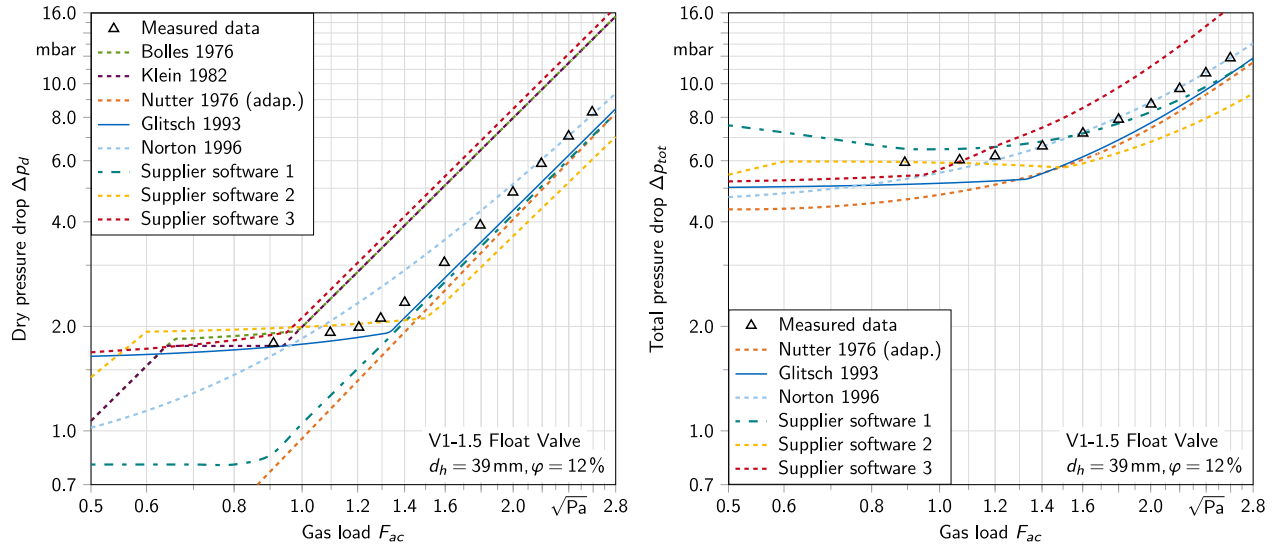


Fig. 2 Pressure drop correlations [4-8] of a V1 float valve tray ($h_{lift} = 8.1$ mm, $\varphi = 12$ %) vs. gas load F_{ac} :
dry pressure drop Δp_d (left) and total pressure drop Δp_{tot} at a liquid load $\dot{V}_L = 16 \frac{m^3}{h}$.

4.2 Froth height

For the froth height, the correlations and measurements of the sieve and the fixed valve trays are depicted in Fig. 3. As explained in section 2, also combinations of clear liquid height and aeration factor can be used as correlations for the froth height, e.g. the clear liquid height model of Hofhuis [10] with an aeration factor model of Stichlmair [2]. Regarding the model of Hofhuis, it should be noted that it was set up for a relative free area of only up to 7 %.

It is clearly visible, that none of the depicted models fits the measured data well. As a validating measurement was carried out via optical control, an incorrectness in the Rapidoscan® measurement technology can be ruled out. For sieve trays (Fig. 3, left), the closest fitting model is that of Stichlmair [2], although large deviations can be observed at higher gas loads. The deviation between this model and the measured data ranges from 4 to 33 %. In the fixed valve case (Fig. 3, right), also the adapted model of Stichlmair is the closest one. This demonstrates that there is still a lot of research needed in this field.

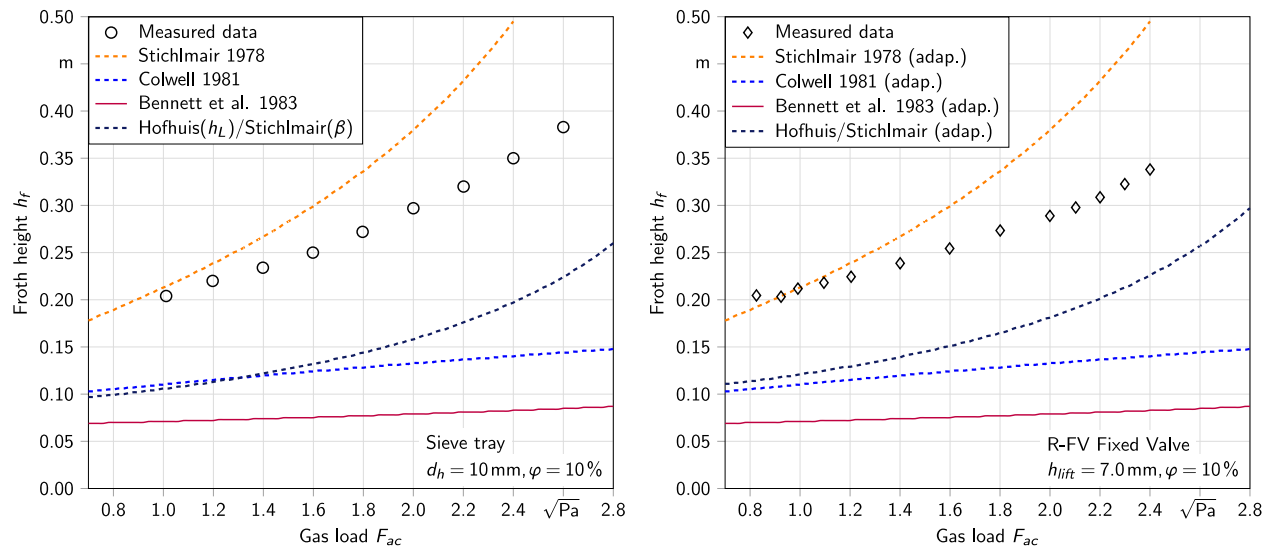


Fig. 3 Froth height correlations [2,3,9,10] vs. gas load F_{ac} at a liquid load $\dot{V}_L = 16 \frac{m^3}{h}$:
sieve tray ($d_h = 10$ mm, $\varphi = 10$ %) (left) and R-FV fixed valve ($h_{lift} = 7$ mm, $\varphi = 10$ %) (right)

4.3 Weeping

In Fig. 4, the comparison of models of the weeping rate with the data obtained from the test rig is shown. In the case of sieve trays (Fig. 4, left), both models are close to the measured data at specific points, but none is a suitable model for the entire curve. For the fixed valves (Fig. 4, right), the adapted literature models do not seem to fit well. Only the fixed valve-specific model of the TrayHeart® software of WelChem [13] provides a reasonably consistent result at lower gas loads. For an appropriate representation of the measured values, further research and detailed model adaptation is needed.

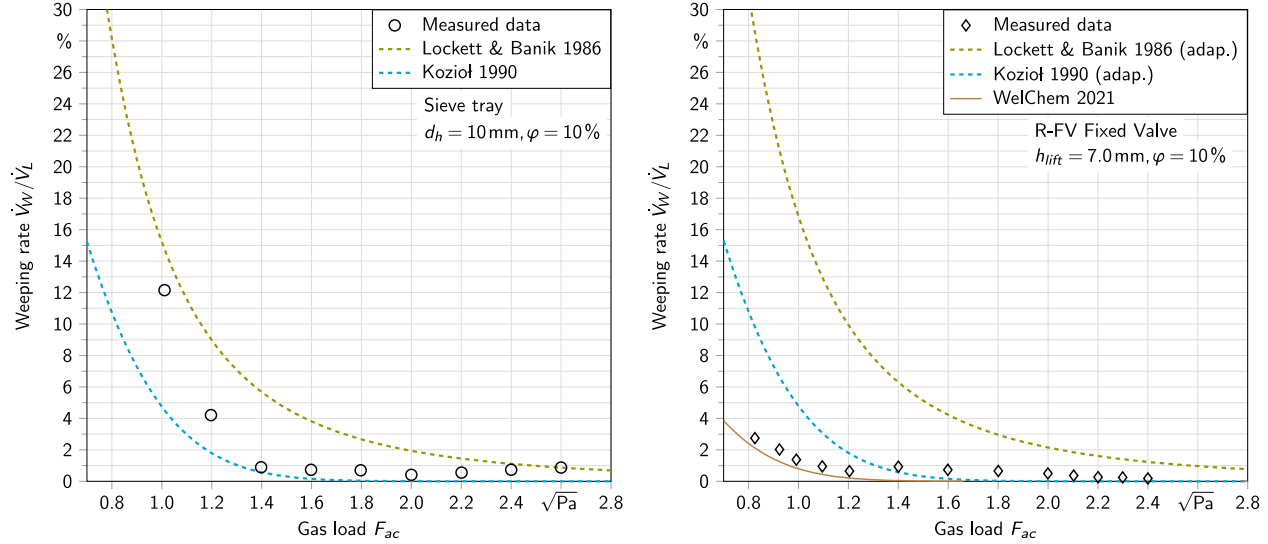


Fig. 4 Weeping correlations [11-13] vs. gas load F_{ac} at a liquid load $\dot{V}_L = 16 \frac{\text{m}^3}{\text{h}}$:
sieve tray ($d_h = 10 \text{ mm}$, $\varphi = 10 \%$) (left) and R-FV fixed valve ($h_{lift} = 7 \text{ mm}$, $\varphi = 10 \%$) (right)

4.4 Entrainment

In Fig. 5, the entrainment measurements of sieve and fixed valve trays are compared with some relevant models from literature. It shows that for the sieve trays (Fig. 5, left), the measured values lie between the curves of the chosen models, but there is no model that fits properly.

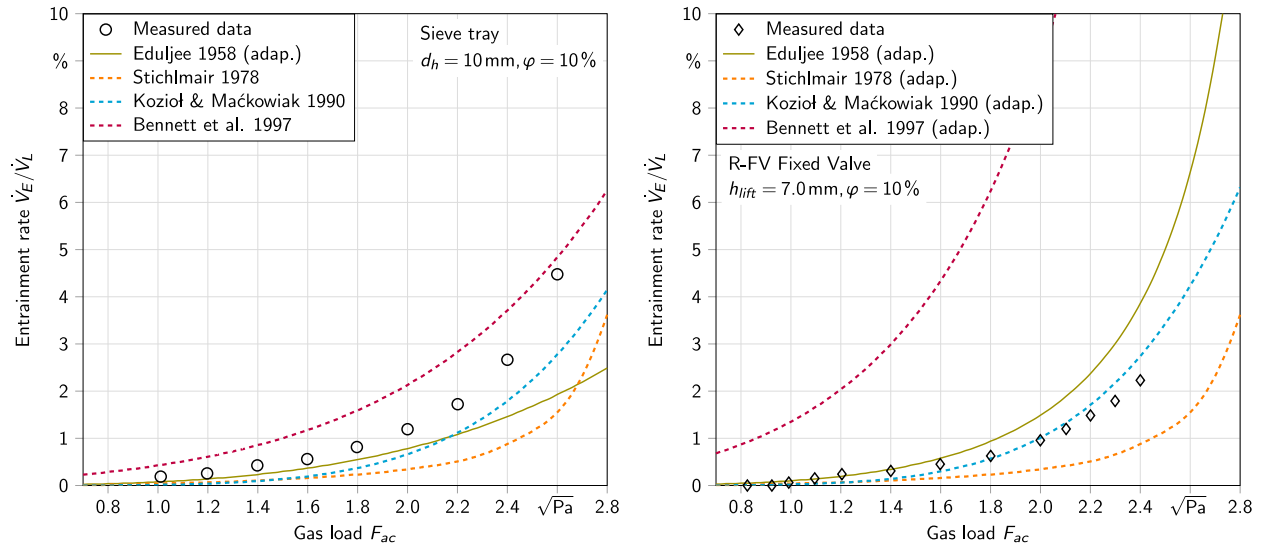


Fig. 5 Entrainment correlations [2,14-16] vs. gas load F_{ac} at a liquid load $\dot{V}_L = 16 \frac{\text{m}^3}{\text{h}}$:
sieve tray ($d_h = 10 \text{ mm}$, $\varphi = 10 \%$) (left) and R-FV fixed valve ($h_{lift} = 7 \text{ mm}$, $\varphi = 10 \%$) (right)

In the case of fixed valve trays (Fig. 5, right), the adapted model of Koziol & Maćkowiak [16] provides the best matching curve at higher gas loads. It is notable, that the adaptation of the models to the fixed valves has very different effects on the different model curves. The extent of the differences shows the influence of the opening area on the models.

5. Conclusions

Although there are numerous model approaches on the hydraulic behavior of trays in the literature, in most cases there is no consensus on which is the best fitting model. As shown in the comparisons in this work, the available models for the parameters pressure drop, froth height, weeping and entrainment show large deviations from each other. Regarding the demand of flexible operation of tray columns due to the increasing power supply from renewable energies, the prediction of the behavior at the load limits is getting increasingly important. For this reason, a suitable hydraulic design is needed that can ensure proper operation of the system and thus results in a proper separation efficiency. This shows that further structured research is required, especially for models describing the behavior at the load limits of trays. Furthermore, there is a particular need for extensive research in the field of fixed valves, as there are few models available and also the adaptation of models needs to be further investigated. For this reason, the presented test rig offers the possibility to investigate numerous effects and hydraulic parameters on a technically relevant scale. Repeatable and automatable measurements for various hydraulic parameters ensure a reliable database for further investigations on high performance trays.

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References

1. Stichlmair, J.; Klein, H.; Rehfeldt, S.: *Distillation: Principles and Practice*. John Wiley & Sons, 2021.
2. Stichlmair, J.: *Grundlagen der Dimensionierung des Gas/Flüssigkeit-Kontaktapparates Bodenkolonne*. Weinheim: Verlag Chemie, 1978.
3. Bennett, D. L.; Agrawal, R.; Cook, P. J.: *New Pressure Drop Correlation for Sieve Tray Distillation Columns*. AIChE Journal **29**,3 (1983), S. 434–442.
4. Bolles, W. L.: *Estimating Valve Tray Performance*. Chemical Engineering Process **72**,9 (1976), S. 43–47.
5. Klein, G. F.: *Simplified Model Calculates Valve-Tray Pressure Drop*. Reprinted courtesy of Chemical Engineering **89** (1982), S. 81–85.
6. Glitsch International: *Ballast Tray Design Manual: Bulletin 4900, Sixth Edition*. Dallas, Texas, 1993.
7. Norton Chemical Process Products Corporation: *Valve Tray Design Manual: English Units*. Akron, Ohio, 1996.
8. Nutter Engineering Co.: *Float Valve Design Manual*. Tulsa, Oklahoma, 1976.
9. Colwell, C. J.: *Clear Liquid Height and Froth Density on Sieve Trays*. Industrial & Engineering Chemistry Process Design and Development **20**,2 (1981), S. 298–307.
10. Hoffhuis, P.: *Flow Regimes on Sieve-Trays for Gas/Liquid Contacting*. Dissertation. TU Delft, 1980.
11. Koziol, A.: *Untersuchungen zum Durchregnen in Siebbodenkolonnen mit Überlauf*. Chemie Ingenieur Technik **62**,10 (1990), S. 864–865.
12. Lockett, M. J.; Banik, S.: *Weeping from Sieve Trays*. Industrial & Engineering Chemistry Process Design and Development **25**,2 (1986), S. 561–569.
13. WelChem Process Technology: *TrayHeart Software, version 4.3.1*. Eichenau, Germany, 2021.
14. Bennett, D. L.; Watson, D. N.; Wiscinski, M. A.: *New Correlation for Sieve-Tray Point Efficiency, Entrainment, and Section Efficiency*. AIChE Journal **43**,6 (1997), S. 1611–1626.
15. Eduljee, H. E.: *Entrainment from Bubble-Cap Distillation Plates*. British Chemical Engineering **3**,9 (1958), S. 474–479.
16. Koziol, A.; Maćkowiak, J.: *Liquid Entrainment in Tray Columns with Downcomers*. Chemical Engineering and Processing **27**,3 (1990), S. 145–153.
17. dieEntwickler Elektronik GmbH: *Rapidoscan Data Sheet RS-C-025-0480-ECT*. Bad Zell, Austria, 2017.