MECHANIKA
CZASOPISMO TECHNICZNE
TECHNICAL TRANSACTIONS
MECHANICS
WYDAWNICTWO
POLITECHNIKI KRAKOWSKIEJ
1-M/2012
ZESZYT 5
ROK 109
ISSUE 5
YEAR 109

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IMPACT OF FOAM TO COLUMN OPERATION

WPŁYW PIANY NA DZIAŁANIA KOLUMNOWE

A b s t r a c t

Foam in process engineering can cause severe problems in distillation and absorption towers which may result in heavy operation problems, reduced capacity and reduced separation efficiency. Foaming behavior cannot be described yet analytically or thermodynamically based on physical properties (density, viscosity, etc.). The dimensioning of packed columns for foaming media in chemical industry or flue gas scrubbing (coking plants, carbon dioxide capture, etc.) in the past was afflicted with oversizing by unfounded safety factors. The invented new foam test device is capable to identify the qualitative foam behavior and intensity in packed columns by two experimental tests - based on systematic results of a pilot plant. The packed column adapted test device will help to identify a potential foam problem and allows prematurely taking respective steps in account.

Keywords: foam, distillation, fluid dynamics, mass transfer columns

S t r e s z c z e n i e

W inżynierii procesowej piana może powodować poważne problemy w wieżach destylacji i absorpcji, czego skutkiem bywają komplikacje natury operacyjnej, ograniczona pojemność oraz zmniejszona wydajność procesu oddzielania. Zachowań piany nie można jak na razie opisywać metodą analityczną lub termodynamiczną na podstawie jej właściwości fizycznych (gęstość, lepkość itp.). Wymiarowanie kolumn wypełnionych dla nośników pianowych w przemyśle chemicznym bądź przemywaniu gazu spalinowego (koksownie, zatrzymywanie dwutlenku węgla itd.) było w przeszłości zawyżone ze względu na bezpodstawne kwestie bezpieczeństwa. Nowo wynaleziona aparatura służąca do testowania piany potrafi określać jakościowe zachowanie piany oraz intensywność w wypełnionych kolumnach drogą dwóch eksperymentów opartych na systematycznych wynikach pracy aparatury pilotażowej. Aparatura kolumny wypełnionej pomoże wykryć potencjalne problemy związane z pianą, pozwalając na podjęcie odpowiednich kroków prewencyjnych.

Słowa kluczowe: piana, destylacja, dynamika płynów, kolumny przeniesienia masowego

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1. Introduction

The appearance of foam in packed columns results in high pressure drop, a lack of mass transfer and unexpected low capacities. Although the dimensioning of packed columns in mass- and heat transfer for non-foaming systems is reliably understood, the dimensioning for potential foaming systems was in the past a challenge associated with uncertainness.

The dimensioning of packed columns for foaming media in chemical industry or flue gas scrubbing (coking plants, carbon dioxide capture, etc.) in the past was afflicted with oversizing by unfounded safety factors. The dimensioning without respective safety factors, foaming in packed columns result in heavy operation limitations up to process shut-down. Alternatively, laborious and costly pilot plant examinations are necessary. However foam occurs, the search and application of a proper foam inhibitor is required.

1.1. Theoretical Background

Foam is a phenomenon which is highly dependent on the physical properties of the system and can occur more or less intense. Mass transfer columns are affected by foam in processes as crude oil, alcohol, organic acid and biodiesel distillation, extractive distillation, amine and sour gas scrubbing (e.g. CO_2 absorption), especially in the presence of liquid hydrocarbons [1-3]. The presence of fine particulate matter can promote foaming as well [4]. A detailed overview with references according to individual applications is given in [5]. Foam can be described by gas bubbles separated between liquid films. The plateau channels are the connection between the foam lamellas and allow fluid exchanges within the foam structure. The presence of surfactants lowers the surface tension, so the gas bubbles gain flexibility as well as stability. Therefore, surfactants and particles can promote foaming.

While some fluids, especially pure liquids do not foam at all [6], other liquids foam more or less intense. The decay time of foams can range from a few seconds until several years – under undisturbed laboratory conditions. The explanation for such a different behavior can be expressed by thermodynamic and mechanical stability considerations, which are based on two fundamental mechanisms.

Due to gravity, the interlamellar fluid drains towards the lower foam layers and thins the upper foam structure out of liquid. When film thickness falls short of a critical laminar thickness respectively a mechanical force appears, this effect results in the destruction of the film layer. While the liquid drainage is destabilizing the gas bubbles and disintegrates the foam layers at the top, this liquid flow stabilizes the lower situated gas bubbles. In mass transfer columns, such a foam-stabilization by replenishing from above is caused by feed and reflux streams.

1.2. Foam in packed columns

Foam in the process industry can cause severe problems in distillation and absorption columns, which may result in increased pressure loss. Therefore, reduced capacity, reduced separation efficiency and the contamination of products in associated process units can be observed. If the process is no longer operable, the complete shutdown causes a corresponding loss of production. Foam problems often cannot or only insufficiently be predicted and prevented before. In addition, foam as the respective cause is often not recognized. In a field study of 31 different failures in mass transfer columns, foam related operating problems ranked with 51 of over 900 cases in 11th place [1].

In distillation and absorption columns, foam can occur in different places, such as in the reboiler, in the base, in liquid distributors or within the packing. In the latter case, there is the possibility that foam is discharged into the bottom or head. The recognition of a foam problem is limited since columns are difficult to observe on sight.

Since the foam potential in columns cannot be predicted yet, the existing industrial solutions for elimination or limitation of a foam problem are over-sizing or the search and usage of foam-suppressing substances.

A comparative analysis of different column internals (trays, centrifugal and structured packings) [7] comes to the conclusion, that the lowest capacity loss occurs in the case of structured packings and that they therefore are ideal for separation processes with foam problems. Although packed columns are under foaming conditions generally more suitable as tray columns, they can still be prone to foam. For the design of packed columns under foaming conditions there are no design advices published. For tray columns, however, there are empirical safety factors depending on the material system and the specific application published [8], but an improved pressure loss calculation is thereby not given.

While in the literature various fundamental studies on the foam stability and destruction can be found, beyond preliminary works carried out at the author's department [2, 9, 10], just a few systematic, scientific studies on the hydrodynamics of foaming media in packed columns were done [11]. In an "Applied Industry Research Foundation" (AiF) project "Foaming media in packed columns" (IGF-no. 16073N), extensive systematic studies on the foam behavior in columns were carried out.

Fig. 1. Foam in random packing McPac #0.75 (left) and foam-flooded column bottom (right) with Triton X-100 30 mg/L at L = 30 m³/m²h and F-factor = 0.5 $Pa^{0,5}$

Rys. 1. Piana w losowo wybranym McPac #0,75 (L) i zalane pianą dno kolumny (P) z Tritonem X-100 30 mg/L przy L = 30 m³/m²h i czynniku F = 0.5 $Pa^{0,5}$

2. Experimental Investigation of foam in packed columns

In this systematic approach, the examination of fluid dynamics on several foaming media was performed with seven packings (dumped and structured) in a scale-up capable packed column with a diameter of 300 mm. Furthermore, fluid dynamic results and foam related phenomenons were found. It turned out, that high capacity packings (high F-factor, high liquid load) are more advantageous towards foam generation than packings with a lower void fraction. Those results served as the basis for the development of new foam test device adapted to packed columns.

2.1. Description of the pilot plant

To ensure the transferability to columns, an appropriately sized pilot plant for the examination of the fluid dynamics of foaming material systems was constructed at the department. The column with a diameter of 300 mm and 2,000 mm packing height for the observation of foam phenomena is made entirely of glass. As shown in the P&ID diagram (Fig. 2), the recycled gas flow in the fully automated pilot plant is controlled with a blower.

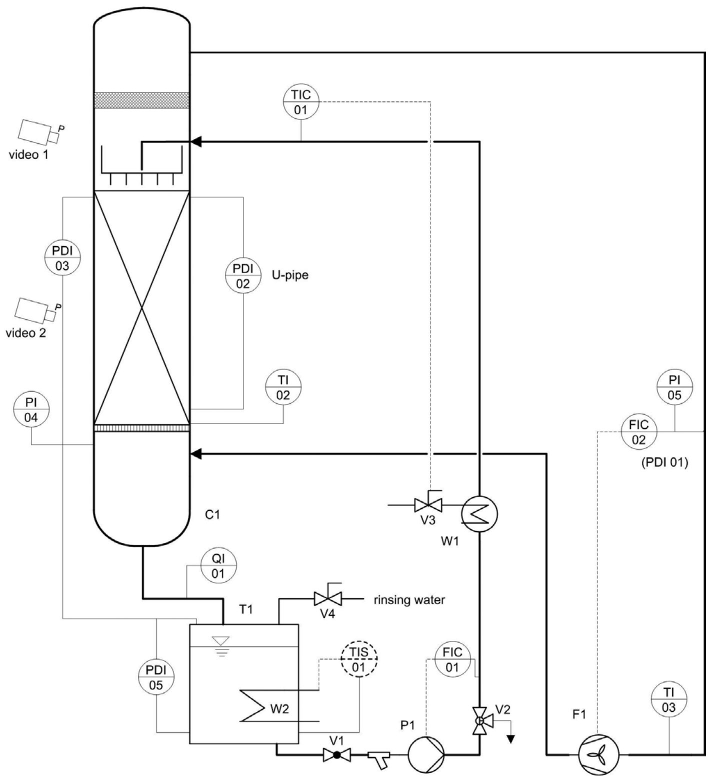

Fig. 2. P&ID scheme of the pilot plant with Ø 300 mm glass column

Rys. 2. Schemat P&ID aparatury pilotażowej ze szklaną kolumną o Ø 300 mm

Seven commercial packings (random and structured, Table 1) are compared according to their respective sensitivity to foaming with several foaming material systems. The operation experiences should provide hints concerning advantageous packing parameters and are used for the upscale of the measurement results of the adapted foam test cell.

The fluid dynamic of various aqueous foaming systems (Table 2) was examined for all packings at liquid loads of L = 0; 10; 30 and 50 m³/m²h. The solutions were prepared with desalinated water (reverse osmosis). It has been found, that some systems weren't foaming in the column at all, although conventional foam test cells predicted a foaming behavior. The aqueous sour gas scrubbing solvent 40 wt.-% (fresh) methyl diethanolamine (MDEA), for example, was been predicted a heavy foaming tendency in the Bikerman-testcell [14] where a liquid sample is aerated by a glass filter. However, column operation wasn't affected by a foam problem at all. Obviously, the conventional testcell leads to false alarms in case of systems with higher viscosity, because the phase separation takes some time.

Table 1

Specification data of the examined packings

packing	type	a [m²/m³]	material	e
Montz-Pak B1-350M	structured packing	350	stainless steel	0.98
Rauschert Hiflow-Ring 15-7	closed random packing	313	polypropylene	0.91
Rauschert Hiflow-Ring 20-4		280	ceramic	0.71
Envimac Mc-Pac #0,75	open random packing	220	stainless steel	0.97
Raschig Super-Ring #0,3		315		0.96
Raschig Super-Ring #1		160		0.98
Raschig Super-Ring #2		98		0.98

Table 2

Examined aqueous material systems

		water	MDEA	butanol	Tego Surten W133 [mg/L]				Triton X-100 [mg/L]	
			40 wt.-%	2 wt.-%	2,5	55	110	550	10	30
r	[kg/m³]	998	1039	993	998	998	998	998	998	998
h	[mPa s]	1.0	8.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0
s	[mN/m]	72.5	55.4	46.2	60.0	45.5	41.7	31.0	58.0	46.0

2.2. Foam Impact on fluid dynamics

It has been found, that even at low specific packing pressure losses flooding phenomena appeared far below reference load limits. Furthermore, by monitoring the process, places of foam formation were identified. As a non-foaming reference system, the results are compared with the system water/air.

For the very low liquid load L = 10 m³/m²h there were no operation limitations with the foaming systems for any packaging at all. The specific pressure drop profiles as a function of the F-factor (equation (1)) are for low gas loads similar to non-foaming systems. At higher liquid loads (L = 30 and 50 m³/m²h) the operation is problematic because of an increase of occurring foam. Especially for packings with a void fraction ε (equation (2)) below 0.97 (in this case the random packings Hiflow-Ring 15-7 and 20-4), a high foam generation was observed which influenced the specific pressure drop over the packing height dramatically.

$$\text{F-factor} = \overline{w}_{Gas}\sqrt{\rho_{Gas}} \tag{1}$$

$$\varepsilon = \frac{V_{total} - V_{Packing}}{V_{total}} \tag{2}$$

For packings with void fractions up from 0.97, an increase of the gas load was getting a problem for the operating conditions.

Interestingly, there were different behaviors concerning the fluid dynamics observed. At the higher liquid loads, L= 30 and 50 m³/m²h, foam often accumulates with this experimental set-up mainly in the column bottom and leads to flooding of the gas inlet (Fig. 1). The continuous liquid flow stabilizes the foam in the bottom. In addition, foam is generated by the reflux impact to the liquid level. The liquid load seems to have a greater impact on foaming than the gas load.

This effect seems to be related on high shear forces at low gas loads (*F-factor* ca. 0.5 – 1 $Pa^{0.5}$). With an increase of the gas load could be observed, that foaming was often reduced. The pressure drop characteristics in relation to the *F-factor* of three packings are shown in Fig. 3-4 for non-foaming and foaming conditions. While the specific pressure loss for low liquid loads as L = 10 m³/m²h is for foaming compared to a non-foaming system for the examined packings nearly identical, the pressure loss under foaming conditions increases strong for the liquid loads. As shown in Fig. 3 (left) the random packing Super-Ring #1 is affected by foam, which results in a higher pressure drop, but the pressure drop characteristic is still comparable to non-foaming conditions. In this case it could be observed, that foam occurred predominantly at the column wall. Inside the packing there was only a little bit of foam visible which could be related to a foam-phase separation. Regarding Fig. 3 (right) for the McPac #0.75 random packing, a quite high foam related pressure drop can be observed even at low *F-factors*. Maybe, the geometric design causes higher shear forces which introduce gas into the liquid phase. Fig. 4 shows the pressure drop characteristic for the structured packing B1-350M. Particular remarkable is the high pressure drop due to a high foam generation rate for low gas loads. For an increasing gas load, this high pressure drop is relative on the decline. It could be observed, that the foam is even disappearing for *F-factors* from 1-2 $Pa^{0.5}$. In this case, the structured packing metal sheets don’t provide a phase exchange possibility if a packing channel is blocked by foam. For higher gas loads from *F-factor* 2 $Pa^{0.5}$ there is an increase of shear forces which leads to an increase of the pressure drop. From this gas load, the pressure drop behavior is comparable to the Super-Ring #1, which means that the foam related pressure is only slightly higher than for non-foaming conditions. In this case, even the capacity isn’t reduced extraordinary.

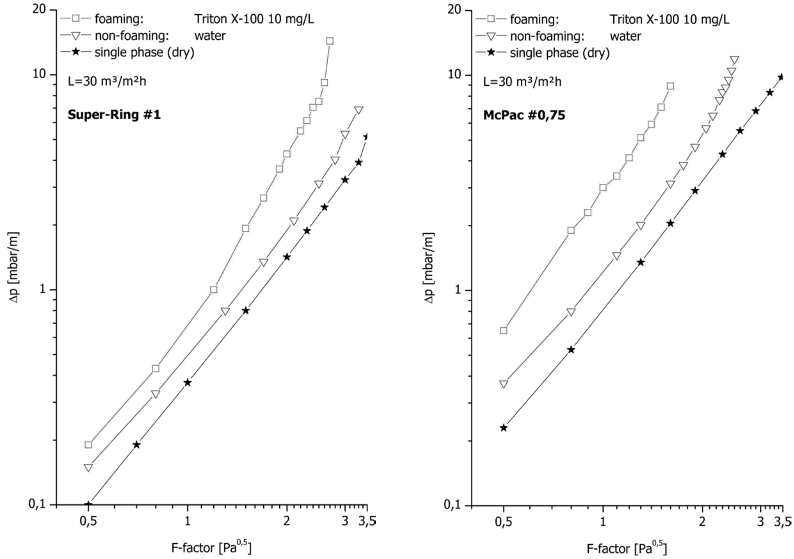

Fig. 3. Pressure-drop characteristics for random packings Super-Ring #1 (left) and McPac #0.75 (right) for non-foaming and foaming conditions at L = 30 m³/m²h

Rys. 3. Charakterystyka spadku ciśnienia dla losowo wybranych Super-Ring #1 (L) i McPac #0,75 (P) w warunkach nie-pianowych i pianowych przy L = 30 m³/m²h

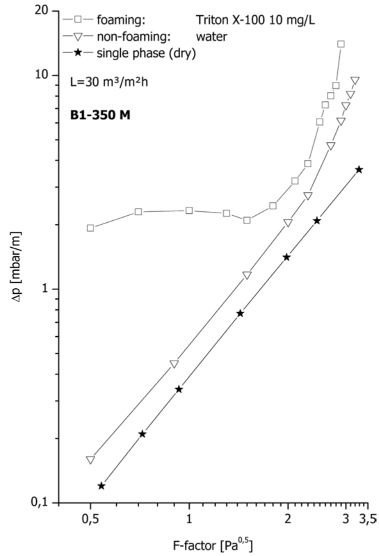

Fig. 4. Pressure-drop characteristics for structured packing B1-350M for non-foaming and foaming conditions at L = 30 m³/m²h

Rys. 4. Charakterystyka spadku ciśnienia dla strukturalnego wypełniania B1-350M w warunkach nie-pianowych i pianowych przy L = 30 m³/m²h

As shown in Fig. 3-4, there is no significantly greater curve increase in the log(Δp)-log(*F-factor*) diagram, as known from non-foaming systems above the stagnation point. Therefore, a direct comparison of a flood point shift is difficult, especially since foam can flood the liquid distributor quite fast. For foaming systems, flooding occurs at a much lower specific pressure loss and in most cases abruptly. It has been shown that the pressure loss development do not directly give hints on the load limits and safe operation conditions. An estimation of an acceptable operating range is therefore not achievable by the pressure loss characteristic.

2.3. Foam Impact on liquid retention time

While in chemical engineering high mixing rates and high surfaces are very welcome for high mass transfer, axial back mixing due to foam has to be prevented in mass transfer columns [13]. Therefore, a qualitative analysis of the retention time has been carried out. A sodium chloride tracer solution was introduced into the feed stream and was monitored in the column base by a conductivity meter. The moment of tracer introduction is measured by the process control system. As non-foaming reference, measurements with water were performed. Three gas loads have been observed. The results for a low (*F-factor* = 0.8 $Pa^{0.5}$) and a high gas load (*F-factor* = 2 $Pa^{0.5}$) are presented in Fig. 5-6 for the above discussed random packings Super-Ring #1 and McPac #0.75 and the structured packing B1-350M. Fig. 5 shows the impact of foam on the liquid retention time for *F-factor* = 0.8 $Pa^{0.5}$. The liquid phase behavior of the Su-

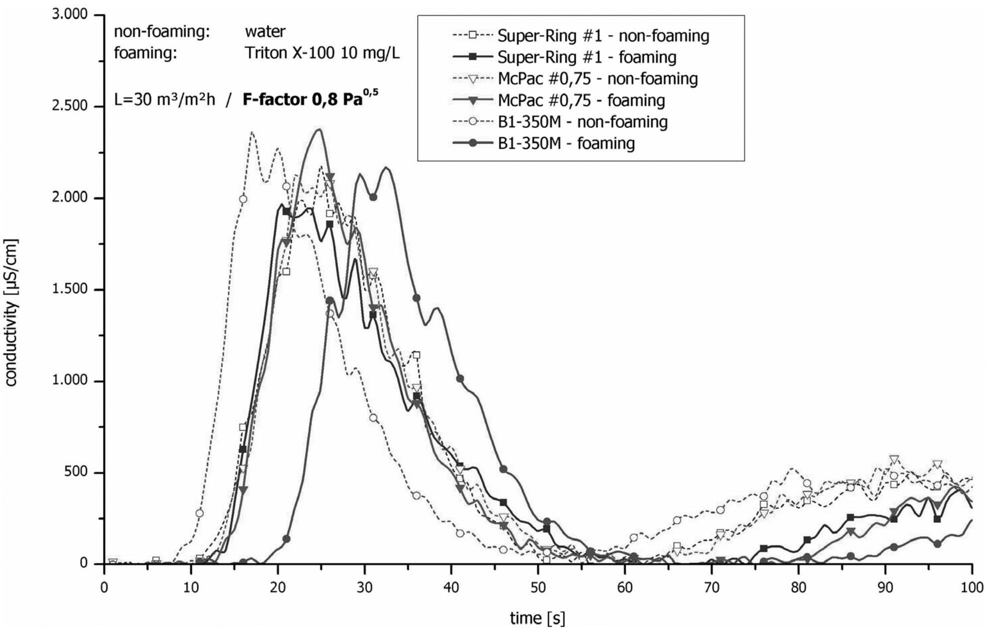

Fig. 5. Impact of foam on liquid retention time at low gas load F-factor = 0,8 Pa0.5

Rys. 5. Wpływ piany na czas retencji płynu przy czynniku F niskiego obciążenia gazowego = 0,8 $Pa^{0.5}$

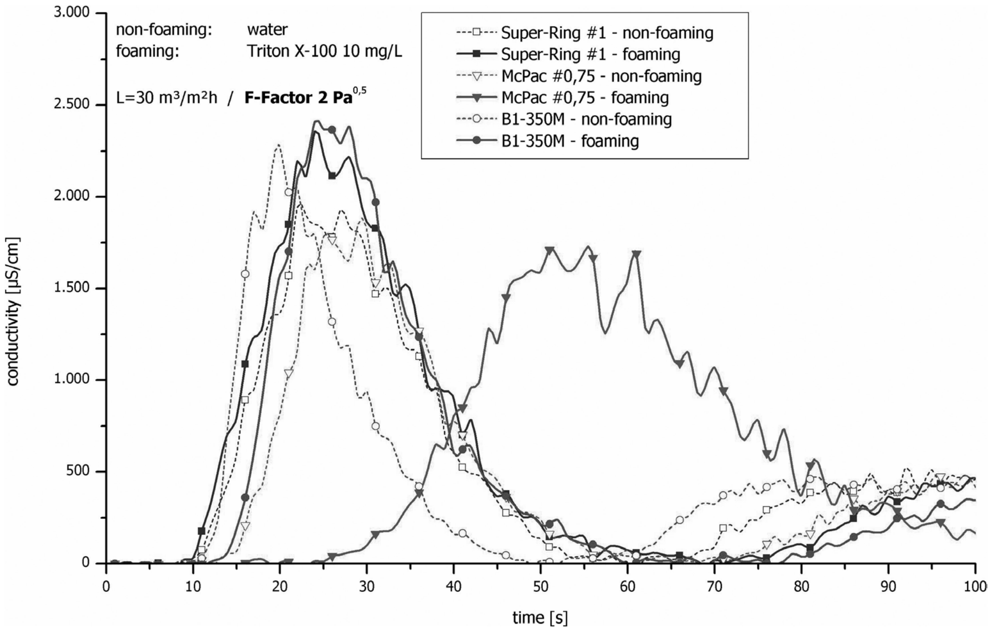

Fig. 6. Impact of foam on liquid retention time at low gas load *F-factor* = 2 Pa$^{0.5}$

Rys. 6. Wpływ piany na czas retencji płynu przy czynniku F niskiego obciążenia gazowego = 2 Pa$^{0.5}$

per-ring #1 and McPac #0.75 experiments doesn't show any noteworthy difference from non-foaming compared to foaming conditions. Regarding the structured packing B1-350M, there is a notable liquid phase delay of ten seconds. This corresponds to the statement concerning the fluid dynamics, where for low gas loads a high foaming rate was observed and which resulted in a high pressure drop. Since there is only a delay of the tracer signal and no significant peak expansion, there is a strong suspicion that for this gas load no relevant back mixing occurs.

Figure6 shows the retention analysis for the higher gas load *F*-factor = 2 Pa$^{0.5}$. Similar to the low gas load, the liquid phase in case of Super-ring #1 isn't notable effected by foam. In contradiction to the low gas load results, here is the McPac #0.75 highly effecting the liquid phase. The liquid is delayed due to foam for ca. 20 seconds and the tracer peak is expanded nearly for the double time. Especially regarding the peak expansion, one can assume that in this case under this loads, foam tends to axial back mixing.

3. Development of a foam test cell for packed columns

Concerning an estimated foam problem in packed columns, up to the present no reliable prediction method was known. Neither is the foaming behavior of a material system estimable based on material parameters nor was an appropriate experimental test device available. Approved foam test devices do not consider the special fluid dynamics of packed columns and the presence of a packing and its influence on shear stress. Furthermore, the foam stabilizing liquid reflux isn't taken in account either. The examinations have shown, that conventional foam test devices are not practical reliable to provide a reliable transferability. The scientific findings of this work confirm the impact of those parameters on the foam behavior in packed columns. This being the situation, the development of a foam test device was carried out by determination of on the foam behavior relevant impact factors.

An adapted foam test cell was developed, which is capable of foam generation by aeration and by a height-adjustable sprinkler. The set-up shown in Fig. 7 is based on a temperature-controlled tank with 80 mm diameter in which a liquid sample can be frothed up by aeration through a glass frit and by sprinkling. The set-up has a wide operating range of (up to 200°C; vacuum) and is resistant to many material systems. The investigation of insertable packing geometries allows the consideration of shear force influence on the foaming behavior.

The results of the fluid dynamic investigations were used as the basis for the development of a new test cell adapted to packed columns. Therefore, the influence of foam on the fluid dynamics of nine material systems (observed in the column) were taken in account. Extensive experimental investigations resulted in the fact, that no single experiment was capable of providing transferability for all material systems on the behavior in the pilot plant. The new approach is based on two experiments and combines the results in a new foam-factor for packed columns. The first experiment is the determination of the foam height of an irrigated liquid sample. A gear pump is circulating the liquid sample at $L = 30$ m³/m²h and a liquid distributor irrigates the sample from a height of 300 mm (Fig. 8 top). The second experiment is the determination of the flooding point reduction of an irrigated and aerated shear element. Therefore, the liquid is irrigating a packing of Raschig-Rings (10x10 mm aluminum) at $L = 30$ m³/m²h while a nitrogen flow is continuously increased until the liquid floods the packing (Fig. 8 bottom).

Fig. 7. New foam testcell

Rys. 7. Nowa aparatura do testowania piany

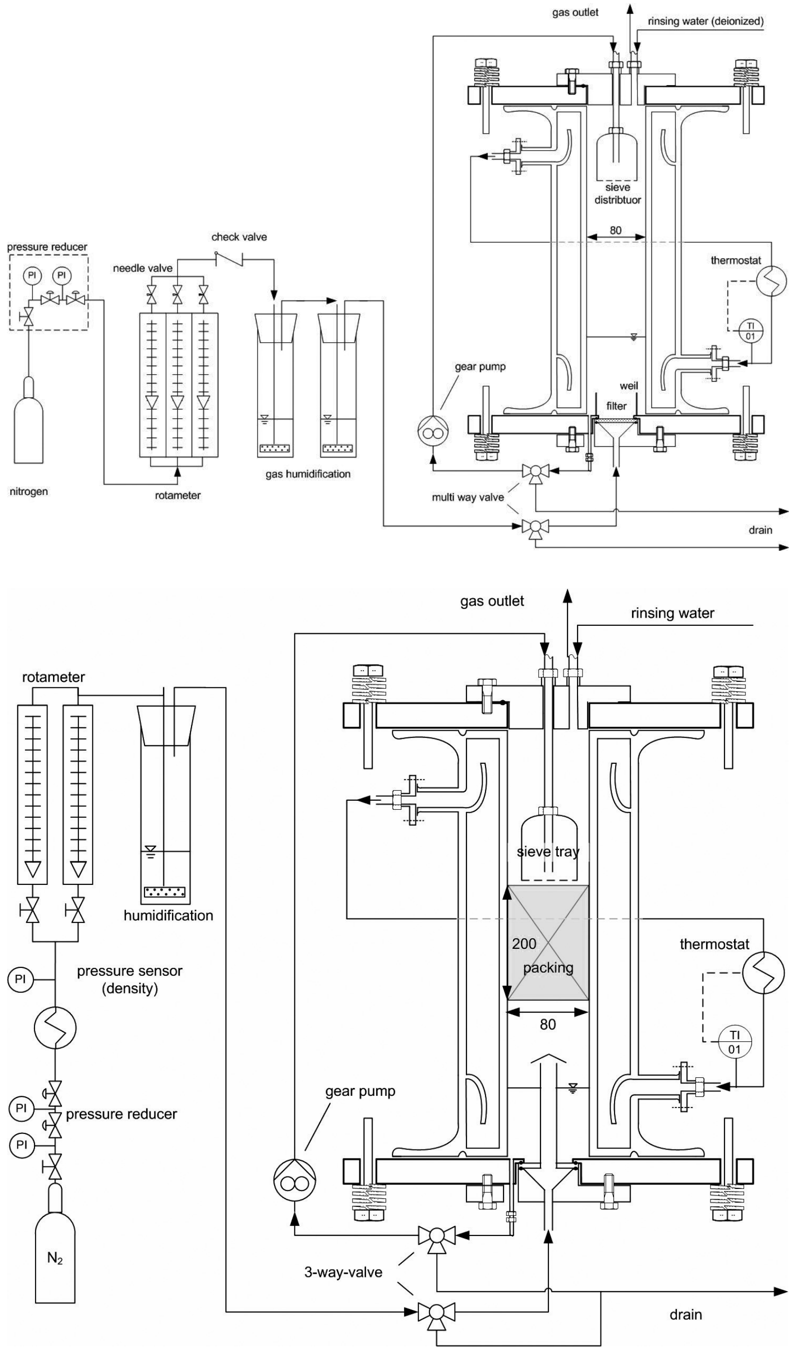

Fig. 8. P&ID schemes of the new foam testcell Ø 80 mm (top: test I, bottom: test II)

Rys. 8. Schematy P&ID nowej aparatury do testowania piany Ø 80 mm (góra: test I, dół: test II)

After performing both experiments, the operator combines both results according to Fig. 9 and equation (3). Depending on respective thresholds of foam height and flooding pint reduction, the result is the so called *foam-factor*.

$$foam - factor = \sqrt{(\text{parameter A } \cdot \text{parameter B})} \tag{3}$$

Its value may turn out between 1.0 and 3.0 where 1.0 is correlated to a non-foaming material system and the maximum of 3.0 to a heavy foaming material system. Values between 1.5 and 2.5 point to a moderate foaming tendency in a packed column. This scale is correlated to the experience of the nine material systems investigated in the pilot plant. In a conventional testcell, the material system MDEA was predicted foaming and the system Triton X-100 10 mg/L produced very stable foam, but in the pilot plant both systems could be operated. Table 3 documents the reliability of the new foam-factor, because even the mentioned material systems which were identified foaming are classified correctly.

Table 3

Examined aqueous material systems

	irrigated liquid sample	flooded irrigated andaerated packing	foam-factor
material system	parameter A	parameter B	$(A \cdot B)^{0,5}$
pure water	1.0	1.0	1.0
Tego Surten 2,5 [mg/L]	1.5	1.7	1.6
MDEA 40 wt. [%]	1.3	1.5	1.4
Butanol 2 wt. [%]	2.1	3.0	2.5
Triton X-100 30 [mg/L]	3.0	3.0	3.0
Tego Surten 550 [mg/L]	1.0	2.6	1.6
Tego Surten 110 [mg/L]	1.0	2.9	1.7
Tego Surten 55 [mg/L]	1.4	3.0	2.0
Triton X-100 10 [mg/L]	3.0	1.0	1.8

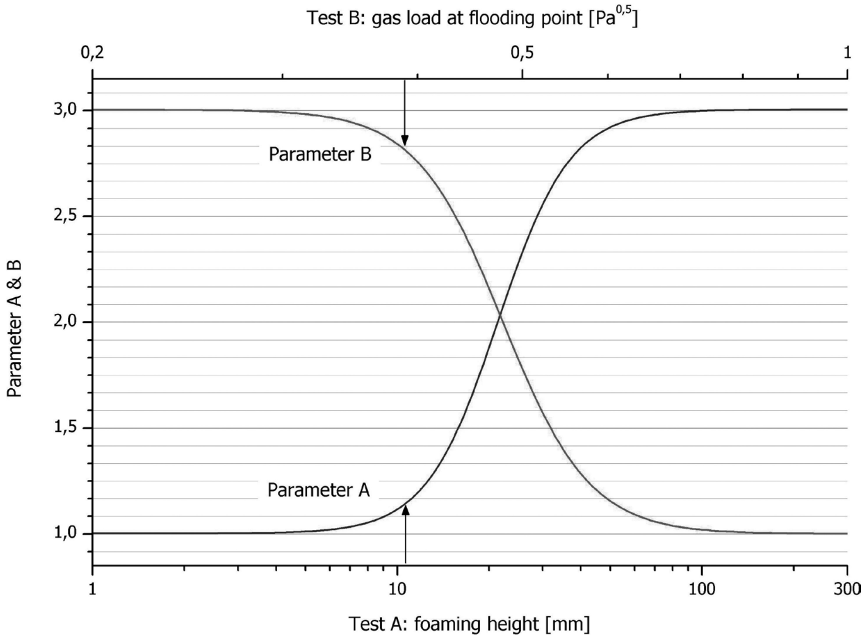

Fig. 9. New foam classification scheme based on the new testcell (tests A and B)

Rys. 9. Wykres nowej klasyfikacji piany w oparciu o nową aparaturę do jej testowania (testy A i B)

4. Conclusions

The examinations have shown, that conventional foam test devices are not practical reliable to provide a reliable transferability. Possible causes hereby were identified as a missing liquid reflux, which stabilizes or destroys foam in packed columns. This being the situation, the development of a foam test device was carried out by determination of on the foam behavior relevant impact factors. The invented new foam test device is capable to identify the qualitative foam behavior and intensity in packed columns by two experimental tests - based on systematic results of the pilot plant. Therefore, in the case of a potential foam problem, the experimental time and effort is highly reduced. The packed column adapted test device will help to identify a potential foam problem and allows prematurely taking respective steps in account.

Symbols

a – specific surface [m^2/m^3]
$\dot{V}$ – volume flow [m^3/s]
L – liquid load [m^3/m^2h]
$\overline{w}$ – gas velocity [m/s]

ε – void fraction
η – dynamic viscosity [mPas]
ρ – density [kg/m^3]
– surface tension [kg/s^2]

The authors gratefully acknowledge the support for the project "foaming media in packed columns" (AiF-no. 16073) by the "Applied Industry Research Foundation" (AiF), by the collaborating enterprises and for the financial support granted by the German Federal Ministry of Research and Technology

References

[1] Kister H.Z., *What Caused Tower Malfunctions in the Last 50 Years?*, Chem. Eng. Res. Des., **81** (1), 2003, 5-26.
[2] Thiele R., Repke J.-U., Diekjakobs B., Thielert H., Wozny G., *A General Rate-Based Model for Industrial Reactive Absorption and Desorption Processes in Sour Gas Treatment*, presentation on AIChE Spring Meeting: Distillation 2005, Topical Conference Proceedings, 197-208.
[3] Zheng Y., Kiil S., Johnsson J.E., *Experimental investigation of a pilot-scale jet bubbling reactor for wet flue gas desulphurization*, Chem. Eng. Sc., **58** (20), 2003, 4695-4703.
[4] Wasan D., Nikolov A., Shah A., *Foaming-Antifoaming in Boiling Suspensions*, Ind. Eng. Chem. Res., **43** (14), 2004, 3812-3816.
[5] Kister H.Z., *Distillation Operation*, McGraw Hill, New York 1990.
[6] Ross S., *Mechanisms of Foam Stabilization and Antifoaming Action*, Chem. Eng. Prog., **63** (9), 1967, 41-47.
[7] Lebedev N., Vladimirov A.I., Kos'min V.D., *Effect of Foaming on Hydrodynamics of Mass-Transfer Contact Devices*, Chem. Technol. Fuels Oils, **33** (6), 1997, 332-334.
[8] Lockett M.J., *Distillation Tray Fundamentals*, University Press, Cambridge 1986.
[9] Thiele R., Brettschneider O., Repke J.-U., Thielert H., Wozny G., *Experimental Investigations of Foaming in a Packed Tower for Sour Water Stripping*, Ind. Eng. Chem. Res., **42** (7), 2003, 1426-1432.
[10] Thiele R., Wiehler H., Repke J.-U., Thielert H., Wozny G., *Hydrodynamics of Foaming Systems in Packed Towers*, presentation on AIChE Annual Meeting 2004, Austin.
[11] Chen G.X., Cai T.J., Chuang K.T., Afacan A., *Foaming Effect On Random Packing Performance*, Chem. Eng. Res. Des., **85** (2), 2007, 278-282.
[12] Bikerman J., *Foams*, Springer, New York 1973.
[13] Valenz L., Rejl F.J., Síma J., Linek V., *Absorption Mass-Transfer Characteristics of Mellapak Packings Series*, Industrial & Engineering Chemistry Research, **50**, (2011), 12134-12142.