Foaming in Wet Flue Gas Desulfurization Plants: Laboratory-Scale Investigation of Long-Term Performance of Antifoaming Agents

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Spontaneous foaming can cause a range of operational problems in industrial processes such as wet flue gas desulfurization (FGD). This work investigates the performance of selected antifoaming agents (Nalco FM-37, Foamtrol 2290, and rapeseed oil) on foams generated by egg white albumin (protein), sodium dodecyl sulfate, and adipic acid at conditions of relevance for wet FGD plants. The addition of antifoaming agents breaks any existing foam and causes an induction period without foaming, after which the foam gradually will begin to reappear. Foaming by egg white albumin (2 g/L) at 0.014 m/s could be controlled by both commercial antifoaming agents (6.4 g/L), but not by rapeseed oil addition. Foaming by pure commercial antifoaming agents has also been demonstrated: up to 7×10^{-2} m foam was observed with 6.4 g/L Nalco FM-37. © 2013 American Institute of Chemical Engineers *AIChE J*, 59: 3741–3747, 2013
Keywords: wet flue gas desulfurization, foaming, antifoaming agent, pH, sodium dodecyl sulfate, protein

Introduction

Stricter emission control legislation on acid gases (SO_2, NO_x, and HCl) is causing more coal and oil-fired power plants to install high-efficiency flue gas desulfurization (FGD) systems, especially wet FGD.[1] In wet FGD plants, the flue gas containing SO_2 and other acidic gases enters the wet FGD absorber and is brought into contact with an alkaline limestone slurry. The SO_2 removal efficiency depends on mass transfer through both the gas and the liquid film. To obtain a saleable gypsum product, most installed FGD capacity uses the wet FGD forced oxidation system.[1] The overall chemical reaction is

$$\mathrm{CaCO_3(s) + SO_2(g) + 2H_2O(l) + \frac{1}{2}O_2(g) \rightarrow CaSO_4 \cdot 2H_2O(s) + CO_2(g)} \quad (1)$$

Foaming problems have been reported at several Danish and international wet FGD plants.[2] Foam is defined as a dispersion of gas in a liquid matrix, forming polyhedral or spherical bubbles, depending on the liquid content.[3] Foaming can be induced by surfactants, which lower the surface tension and help stabilizing the foam by providing a restoring liquid flow toward locally thinned regions, so called Gibbs–Maragoni effect, or by polymers/macromolecules, which form a viscoelastic network that enhances the mechanical stability of the lamella, increases surface and liquid viscosity, and slow down thinning of the lamella.[4] Finally, electrostatic and/or steric stabilitation of the lamella can be of importance.

Foaming in wet FGD plants can interfere with process monitoring equipment for the liquid level and slurry density control. This can result in gypsum scaling, excessive solid concentrations, carryover of slurry into the duct work and the booster fan[2] and potential cavitation of recycle pumps. However, foaming may also provide an increased interfacial area for SO_2 absorption—especially when the flue gas is bubbled through the slurry (e.g., in a jet-bubbling reactor).[5] When discovered, foaming can be controlled by addition of antifoam, but the required dosage and the effect time can vary from one incident to the next. Defoamer can be added to break existing foam, whereas antifoaming agents are used to prevent the formation of foaming. However, most formulations are capable of both destroying existing foam and preventing the appearance of additional foaming. Commercial antifoams are complex formulations consisting of oils, hydrophobic particles, and a range of other additives.[6] These formulations remove and prevent foaming by spreading fluid entrainment, increased drainage of the foam lamella, and lamella breakage. For explanatory purposes, the antifoaming mechanisms are classified by the entry (E), spreading (S), and bridge (B) coefficients (Eq. 2–4).[7]

$$E = \delta_{AW} + \delta_{OW} - \delta_{OA} \quad (2)$$

$$S = \delta_{AW} - \delta_{OW} - \delta_{OA} \quad (3)$$

$$B \equiv \delta_{AW}^2 + \delta_{OW}^2 - \delta_{OA}^2 > 0 \quad (4)$$

A negative entry coefficient corresponds to full immersion of a droplet inside the aqueous foam phase and thereby poor antifoaming activity. A positive entry coefficient corresponds

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to the potential formation of oil bridges through the foam film, but other factors such as a low entry barrier are also necessary to obtain an efficient antifoaming performance. A positive bridging coefficient corresponds to unstable bridges and thereby foam breakage through film rupture. A positive spreading coefficient means that an antifoaming oil lens will spread on the film surface and thereby dragging water away causing local film thinning and potential rupture. This may furthermore benefit the antifoaming potential by reducing entry barriers, supplying oil to oil bridges, and by exposing solid particles capable of surfactant adsorption. Further details and a thorough review of the current status of antifoam research can be found in Denkov[7] and Karakashev and Grozdanova.[8]

Operational problems due to foaming also occur in other industrial processes, for example, wastewater treatment process, amine scrubbing, pulp processing, and distillation processes.[9,10] Nevertheless, foam can also contribute with desired effects in, for example, brewing industry, healthcare products, and ore separation processes by flotation.[3] Several fundamental studies of foaming and antifoaming mechanisms have been published in the literature,[3,7,11] alongside a few studies of foaming in specific industrial processes (sour water stripping[9] and particles, electrolytes, and buffers in wet FGD[12]). However, no previous investigations of the long-term performance of foaming agents [sodium dodecyl sulfate (SDS) and protein] and antifoaming agents at wet FGD conditions have been found in the literature.

In this work, the effects of selected antifoams, having potentially both antifoam and defoamer properties, on foaming agents relevant for wet FGD in experiments lasting up to 110 h are studied. The influence of pH, salt concentration, and gypsum concentration on the foamability (initial foam height caused by foaming agent)[7] and foam stability (persistence/lifetime of foam layer) is furthermore investigated.

Strategy of Investigation

This investigation of foaming and antifoaming agents at wet FGD conditions has been carried out by Bikerman experiments. SDS (technical grade, Riedel-de Haeen AG), egg white albumin (Sigma-Aldrich, grade II), and adipic acid (Bie & Berntsen AS, analytical grade) were chosen as foaming agents. SDS is a powerful classic surfactant and the most commonly used foaming agent in the foaming literature.[3,7,13] Under normal operational conditions, SDS is not present in wet FGD plants, but is used in this investigation to represent a strong and persistent foaming agent. Potential organic contaminations and unexpected impurities in wet FGD plants can lead to the presence of such powerful foaming agents, which makes SDS an important part of this study. In addition, SDS has been used in many other studies on foaming in various types of process equipment, and therefore, the long-term results of this work may also have comparative relevance to engineers and researchers in other fields. Protein-induced foaming (e.g., when biological material degrades in lakes and seas) has been experienced within various industrial processes, for example, in waste water treatment plants and fermentation process.[14] Bacterial growth within wet FGD plants has been reported for makeup water, scale deposits, and the warm (about 50°C) wet FGD slurry.[15] These microbial communities may release macromolecules and proteins during degradation, thereby introducing foaming agents to the system. For wet FGD plants in Denmark, there have been several foaming incidents ascribed to protein-induced foaming. As an example, large volumes of wet FGD slurry are stored during maintenance of the wet FGD plants, leaving time for bacterial growth, often causing foaming, overflow to ductwork and flooding of the surrounding area, when the slurry is returned to the wet FGD holding tank. Elevated bacterial/biological activity in those slurries was detected by a test kit and a distinct unpleasant odor was also noted. It has also been suggested that dissolved ammonia, from the selective catalytic reduction (SCR) process, could contribute to bacterial growth and protein release.[2] Protein is, therefore, a likely foaming candidate in wet FGD plants. Industrial samples, collected from wet FGD plants experiencing foaming, could have been used to provide the protein foaming candidates. However, the versatile microbial communities in such solutions are very difficult to map and quantify and a generalization of the results would be difficult. For the purpose of a long-term study of the performance of different antifoaming agents, well-defined commercial foaming agents are preferred. Consequently, egg white albumin was chosen as a representative for protein foaming in wet FGD plants based on availability and its previous use in other protein foaming studies.[16] Adipic acid is often used as a wet FGD additive to improve SO_2 removal efficiency,[17] but it may also act as a weak foaming agent.[12] The two commercial antifoams [Nalco FM-37(Nalco) and Foamtrol 2290 (GE Power and Water)] and one vegetable oil (rapeseed oil, Sigma-Aldrich) have been chosen for this work. The two commercial antifoams have been used by American wet FGD plants[2] and vegetable oils have been used on many occasions in Danish wet FGD plants due to low price and high availability.

The conditions of the experiments performed, shown in Table 1, have been chosen to simulate process conditions in wet FGD plants. The pH values encountered in wet FGD plants can range from 3 to 6 in the absorber, 4–6 in the holding tank, and 9–10 in the limestone preparation units.[1,18] Foaming in wet FGD plants may be facilitated by stirring, air injection (0.01 m/s) as well as the flue gas flow (0.13 m/s), which in the jet bubbling outline passes through the slurry.[5] The wet FGD slurry will contain considerable levels of ions from reactant dissolution (Ca^{2+}, Mg^{2+}, Na^+, and some impurities) and species (SO_4^{2-} and Cl^-) from SO_2 and HCl absorbed from the flue gas.[19] Ca^{2+} from limestone and Cl^- from the flue gas are present in the highest concentrations (Cl^- will constitute 70–80% of the molar anionic concentration)[20] and $CaCl_2$ has, therefore, been chosen as a representative wet FGD electrolyte. A slurry Cl^- concentration of 5 g/L, representative of co-combustion with biomass, where Cl^- originates from KCl in the plant material, has been used in this work. A chloride concentration of 25 g/L is representative of pure coal combustion.[17]

Experimental Setup and Procedure

Bikerman experimental setup

Figure 1 shows the experimental setup consisting of a Bikerman column and three humidifiers. The Bikerman setup consists of a glass column equipped with a porous sintered glass disc at the gas inlet to generate bubbles ($\sim 10^{-3}$ m diameter). The column diameter ($D_I = 0.07$ m) ensures negligible "wall effects" on foam rigidity and drainage rate.[21] To make long-term experiments possible (up to 110 h), the gas supply (dry air) passes through three humidifiers (1, 1, and

Table 1. Overview of the Experiments Performed and the Operating Conditions Selected

Experiment	Foaming Agents (g/L)		Antifoaming Agent (g/L)		Flow Velocity (m/s)	pH	Gypsum (g/L)	Cl^- (g/L)	Duration Time (h)
1	0.005	SDS	–	–	0.014	–	–	–	<1
2	0.005	SDS	>50	Rapeseed oil	0.014	–	–	–	<1
3	0.005	SDS	55.9	NALCO FM-37	0.005[a]	–	–	–	22
4	0.005	SDS	10.4	NALCO FM-37	0.005	–	–	–	93
5	0.005	SDS	22.2	Foamtrol 2290	0.005	–	–	–	25
6	0.005	SDS	56	NALCO FM-37	0.014	–	–	–	<1
7	2	Albumin	>50	Rapeseed oil	0.014	–	–	–	<1
8	2	Albumin	–	–	0.014	6.5	–	–	<1
9	2	Albumin	12.9	NALCO FM-37	0.014	5.8	–	–	30
10	2	Albumin	6.4	NALCO FM-37	0.014	–	100	–	30
11	2	Albumin	6.4	NALCO FM-37	0.014	5.8	–	–	30
12	2	Albumin	6.4	NALCO FM-37	0.014	5.8	–	–	30
13	–	–	6.4	NALCO FM-37	0.014	5.8	–	–	30
14	2	Albumin	6.4	Foamtrol 2290	0.014	6.8	–	–	30
15	–	–	6.4	Foamtrol 2290	0.014	6.8	–	–	30
16	2	Albumin	6.4	NALCO FM-37	0.014	4.5	–	–	30
17	2	Albumin	6.4	NALCO FM-37	0.014	4.5[b]	–	–	30
18	2	Albumin	6.4	NALCO FM-37	0.014	6.8	–	5	30
19	2	Albumin	–	–	0.014	6.5	–	5	<1
20	1.5	Adipic acid	–	–	0.02	–	–	–	5
21	1.5	Adipic acid	–	–	0.02	–	–	–	13
22	1.5	Adipic acid	0.05	Rapeseed oil	0.02	–	–	–	100
23	1.5	Adipic acid	0.05	Rapeseed oil	0.02	–	100	–	50

[a]Initial velocity = 0.014 m/s (for <30 s).
[b]pH increased to 9.8 (by NaOH addition) the last minutes of the experiment.

0.5 L, respectively) to minimize evaporation of water in the Bikerman column. The Bikerman method is a simple, reproducible, and quantitative way to estimate foaming ability and stability.[13] It is a dynamic foaming measurement technique, in which foam height is determined by a dynamic equilibrium between bubble formation and collapse rate. The Bikerman coefficient ($\Sigma = H/v$) expresses the average bubble lifetime in the foam before it bursts, the coefficient is independent of gas flow rate provided that evaporation (low gas velocities) or rupture of the lamella (high gas velocities) is not significant.[22]

Experimental procedure

Before each experiment, the column was thoroughly cleaned with a soap solution (Blumøller A/S), subsequently flushed with water several times and dried. The foam height of pure water was tested before each experiment as a reference measurement and tests with 1.5 g/L adipic acid were used to measure foam height to ensure that no accumulation of antifoaming agents took place. Each experiment begins by adding a predissolved solution (100 mL stirred for 1 h) of foaming agents to the Bikerman column, filling the humidifiers with water, and starting the gas flow. A carefully controlled amount of antifoams may be added initially or after stable foam has been obtained depending on experimental conditions. In this investigation, Nalco FM-37 (oil-based), Foamtrol 2290 (silicone-oil based), and rapeseed oil have been used as antifoaming agents. The influence of pH (pH adjustment by HCl (Fluka) and NaOH, (Bie & Berntsen), salt concentration ($CaCl_2.2H_2O$, Brenntag Nordic A/S), and gypsum particles (from pilot plant)[23] on albumin foam stability has furthermore been studied. The relative humidity at three locations in the freeboard of the Bikerman column was initially measured with a Testo 635 thermo hygrometer to verify that the saturated gas stream ensures a high relative humidity in the freeboard and thereby negligible evaporation, which otherwise could affect the foam produced by the Bikerman method.[8]

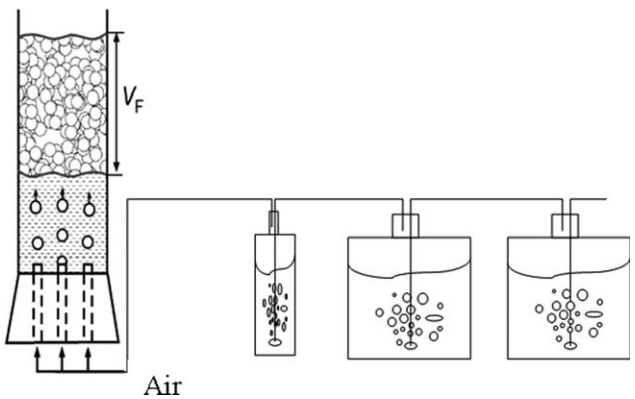

Figure 1. Experimental setup consisting of Bikerman column (left) and humidifiers.

Results and Discussion

Three foaming agents (SDS, protein, and adipic acid) have been tested with two types of commercial antifoams (oil-based Nalco FM-37 and silicon-oil based Foamtrol 2290) and one vegetable oil (rapeseed oil). The influence of pH and chloride concentration on albumin foaming behavior is furthermore investigated. Details of experimental conditions can be found in Table 1.

Effect of relative humidity in the free board

Table 2 shows the relative humidity measured at three locations in the freeboard of the Bikerman column. A high relative humidity was observed above the liquid/foam surface (above 94%) and throughout the freeboard (above 87%). The evaporation rate from the foam surface at these levels of relative humidity will be very slow, as it has also been demonstrated for

Table 2. Relative Humidity (RH) at Three Positions in the Bikerman Freeboard Measured by a Testo 635 Thermo Hygrometer

Conditions	0.1 L Purified Water		Exp.16	Exp.20
Gas velocity (m/s)	0.02	0.005	0.14	0.02
RH laboratory	51.8 ± 2.7	45.6 ± 2.1	46.8	59.2 ± 6.4
RH 0.5×10^{-2} m above liquid surface	99.9 ± 0	99.9 ± 0	99.9 ± 0	99.9 ± 0
RH 15.5×10^{-2} m above liquid surface	97.3 ± 0.4	95.0 ± 0.8	94.7 ± 1.1	95.4 ± 1.4
RH 25.5×10^{-2} m above liquid surface[a]	96.9 ± 0.9	87.1 ± 1.8	94.3 ± 0.7	94.7 ± 1.1

Experimental conditions are provided in Table 1.
[a]3×10^{-2} m from top of freeboard.

water evaporation from a horizontal film,[24] and evaporation, therefore, does not affect foam stability.

Performance of antifoaming agents on SDS foaming

SDS is a powerful foaming agent capable of producing considerable foam volumes, especially at 1.5–2 times the critical micelle concentration where the surfactant foamability peaks.[4] Swift overflow, corresponding to a Bikerman coefficient above 19 s, can also occur at lower SDS concentrations (0.005 g/L), even in the presence of antifoaming agents (56 g/L Nalco FM-37) at a gas velocity of 0.014 m/s. Figure 2 shows the foaming behavior of 0.005 g/L SDS solutions with two commercial antifoams (Nalco FM-37 and Foamtrol 2290) at a lower flow velocity (0.005 m/s). The total height of the different foaming solutions and their foam layers are compared to the height of nonfoaming demineralized water, which corresponds well to the height of the liquid phase below the foam layer in foaming solutions (there is only a small difference of about 0.5×10^{-2} m). Initially brief foaming may still occur (up to 0.2 m), but the antifoams break the foam within a few minutes and prevent it from reappearing for at least 7 h. A limited extent of foaming returned after 20 h in the case of high Nalco FM-37 concentrations (56 g/L), which potentially could be caused by the antifoaming agent itself (see Figure 3), as it also has been reported in the literature.[8] Addition of high levels of rapeseed oil (>50 g/L) was unable to affect SDS foaming and overflow swiftly occurred (<30 s).

Performance of antifoaming agents on albumin foaming

In order for albumin foaming to occur, it must adsorb on the gas–liquid interface, adjust its structure, and form a viscoelastic network, which can increase the elasticity and the viscosity of the lamella, and introduce steric interactions across the lamella.[4] The albumin solution was prestirred for 1 h to ensure a good mixing and full dissolution. Without antifoam addition, overflow occurred within 16 s for a 2 g/L albumin solution at a flow velocity of 0.014 m/s, demonstrating a strong adsorption to the gas–liquid interface and formation of a foam stabilizing viscoelastic network.

Figure 3 shows the total liquid and foam height of two experiments with 2 g/L albumin and 6.4 g/L Nalco FM-37 demonstrating a similar induction time (~50 min) and development in foam height as a function of time. After approximately 2 h the foam peaked, followed by a rapid decline and the onset of an additional increase in foam height after approximately 3 h and a stabilization ($8–11 \times 10^{-2}$ m foam) after approximately 7 h. Attachment of albumin particles to the walls of the Bikerman column is observed as the experiment progresses, but this only had a limited effect ($\sim 1 \times 10^{-2}$ m lower) on foam height (verified by washing the column walls).

An increased antifoam dosage (12.9 g/L Nalco FM-37) prolonged the induction time to 5 h and increased the resulting maximal foam height to 16×10^{-2} m, but the overall development was similar. Pure antifoam (6.4 g/L) causes an initial peak in foam height similar to when mixed with albumin solution, but subsequently declines without another increase in foam height. Antifoams when used in high concentrations have previously been reported in the literature to act as foamers/foam stabilizers.[4] The stable foam height that develops with time for albumin and Nalco FM-37 mixtures,

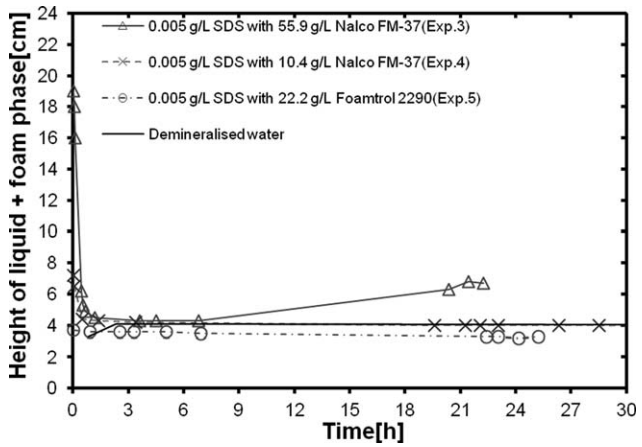

Figure 2. Foaming behavior SDS (0.005 g/L) with two commercial antifoams (Nalco FM-37 and Foamtrol 2290) at a flow velocity of 0.005 m/s.

Experimental conditions are provided in Table 1.

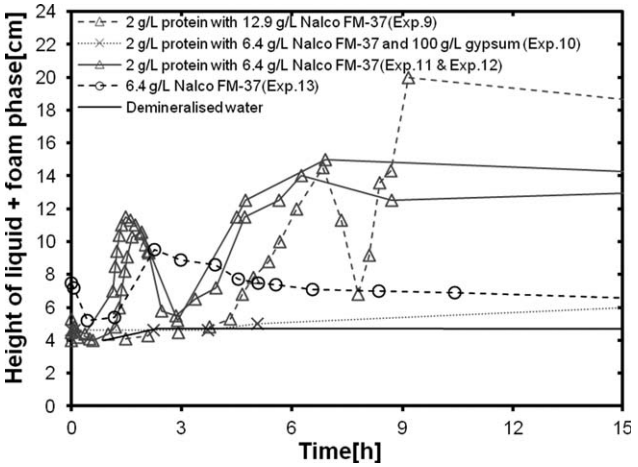

Figure 3. Foaming behavior of protein solution (2 g/L) with Nalco FM-37 (6.4 g/L (two experiments) and 12.9 g/L) and pure 6.4 g/L Nalco FM-37 at a flow velocity of 0.014 m/s.

Experimental conditions are provided in Table 1.

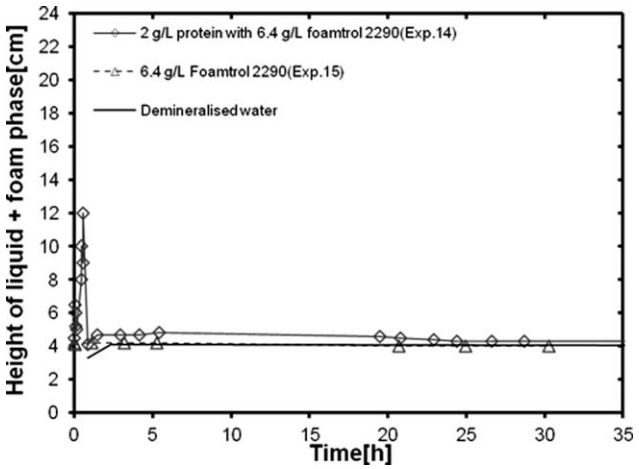

Figure 4. Foaming behavior of protein solution (2 g/L) with Foamtrol 2290 (6.4 g/L) at a flow velocity of 0.014 m/s.

Experimental conditions are provided in Table 1.

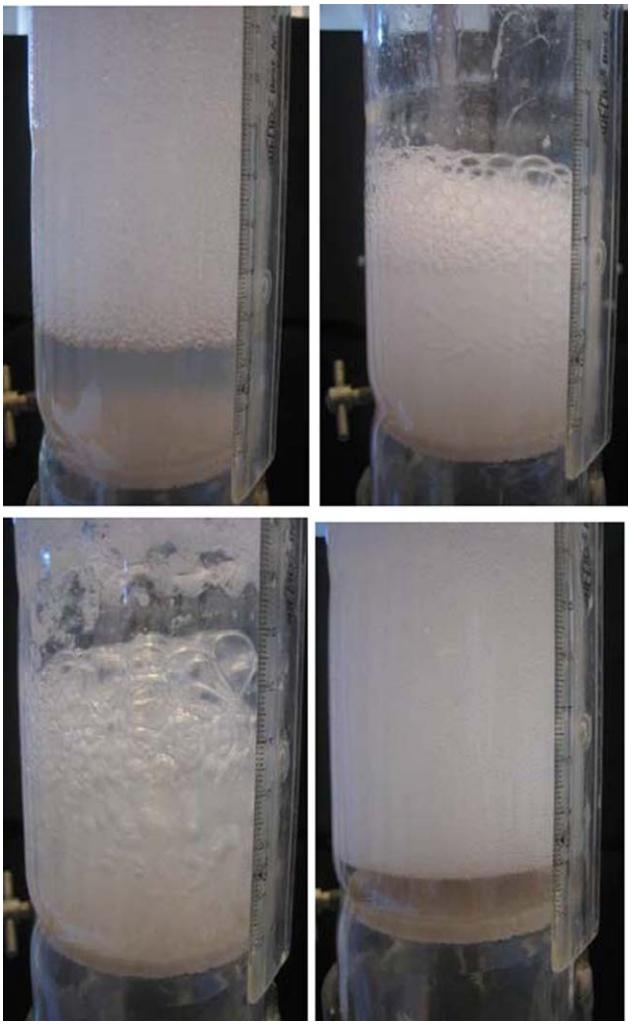

Figure 5. Foam structure for 2 g/L protein (top left), 2 g/L protein with 6.4 g/L Nalco (top right), 2 g/L protein with 6.4 g/L Foamtrol 220 (below left), and 0.005 g/L SDS (below right).

Experimental conditions are provided in Table 1. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

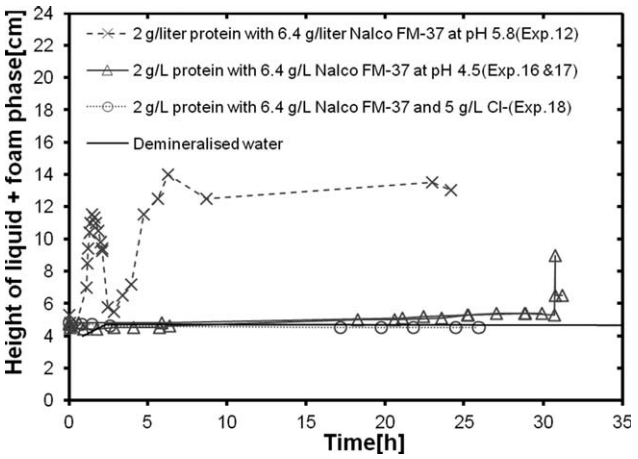

Figure 6. Foaming behavior of protein solution (2 g/L) with Nalco FM-37 (6.4 g/L) at pH 4.5 (two experiments) and 5.8–6.8 with and without 5 g/L Cl.

Experimental conditions are provided in Table 1.

therefore, seems to be caused by a loss of antifoaming activity and the resulting albumin foaming with some foaming contribution from the antifoaming agent. The presence of gypsum particles (100 g/L), and thereby also approximately 1 g/L dissolved SO_4^{2-}, alongside Nalco FM-37, limited the foam layer to $< 2 \times 10^{-2}$ m and prevented the sequence of foam growth and decline observed in the absence of particles.

In Figure 4, two experiments show the foam height of albumin (2 g/L) with Foamtrol 2290 (6.4 g/L) and pure Foamtrol 2290 (6.4 g/L). A very limited initial foam peak, resembling albumin foaming (bubble size 1–2 $\times$ 10^{-2} m Figure 5), is seen for albumin with Foamtrol 2290, but no subsequent foaming behavior is observed for 30 h. Rapeseed oil addition to a 2 g/L albumin solution has no beneficial effect and overflow occurred within 30 s. Figure 6 shows the foaming behavior of albumin (2 g/L) with Nalco FM-37 (6.4 g/L) at pH values from at 4.5 to 5.8 with and without 5 g/L Cl^-. A pH value close to the isoelectric point (IEP) of albumin (4.7)[25] generated no foaming; however, a subsequent

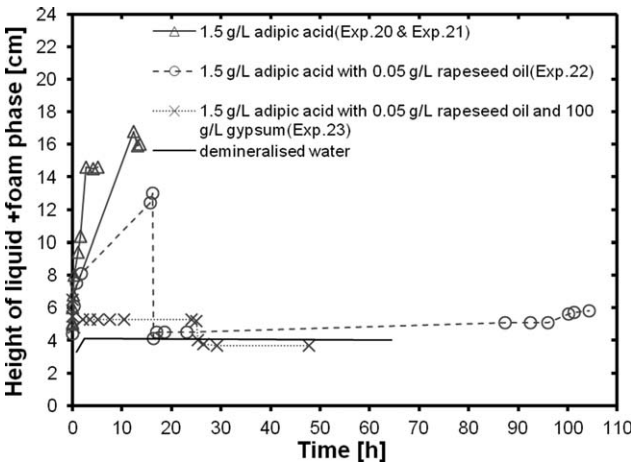

Figure 7. Foaming behavior of adipic acid (1.5 g/L) with Rapeseed oil test (0.05 g/L) at flow velocity of 0.02 m/s.

Experimental conditions are provided in Table 1.

increase in pH (9.8) as the last part of Experiment 17 briefly restored the foamability. Both minimum and maximum foamability near protein IEP have been reported in literature, depending on molecular structure, adsorption behavior, and aggregation.[25] Higher foamability at IEP can be caused by increased protein adsorption at the interface, due to the lower surface charge/higher hydrophobicity.[26] Lower foamability at IEP can be caused by protein precipitation, and by weaker repulsion between surfaces due to compaction of the "hydrophilic" parts of the molecule.[25] A 2 g/L albumin solution with 5 g/L Cl^- and no antifoam agent overflowed within 30 s, but addition of 6.4 g/L Nalco FM-37 prevented any foam from appearing.

Performance of antifoaming agents with adipic acid foam

Adipic acid is a weak foaming agent consisting of two acid groups connected by a short hydrocarbon chain. Figure 7 shows the foaming behavior of 1.5 g /L adipic acid with and without 100 g /L gypsum (addition of 0.05 g/L rapeseed oil after 16 and 25 h, respectively). The foam height of the adipic acid solution stabilizes at 9–12 $\times$ 10^{-2} m within 15 h at a velocity of 0.2 m/s. A high flow rate is necessary because of the limited foaming potential of adipic acid. The addition of a low concentration of a weak antifoaming agent (0.05 g/L rapeseed oil) is able to control foaming for at least 90 h. The addition of gypsum (100 g/L) decreased the foam height to $<2 \times 10^{-2}$ m and this limited foam layer disappeared after antifoam addition. Summarizing, the presence of gypsum particles has a considerable boosting effect on the destabilizing behavior of antifoams added to the slurry.

Conclusions

A series of long-term laboratory-scale foaming and antifoaming tests have been conducted in a Bikerman column connected with a humidified gas stream. SDS, egg white albumin (protein), and adipic acid are used as foaming agents. SDS is the most powerful surfactant of these three foaming agents, albumin also possesses considerable foaming potential and adipic acid may act as a weak foaming agent.[17] Both pure SDS and egg white albumin (0.005 and 2 g/L, respectively) caused foam overflow within a few seconds at a flow velocity of 0.014 m/s. Adipic acid possessed a limited foaming potential and was only tested at high flow rates (0.02 m/s) forming a 9 $\times$ 10^{-2} m to 12 $\times$ 10^{-2} m foam layer.

Vegetable oil is often used as an antifoaming agent in Danish full-scale wet FGD plants, but in this work it only proved efficient for a weak foaming agent, but did so for prolonged periods of time (90 h). No effect of rapeseed oil on either SDS or albumin foaming was observed even at high concentrations (>50 g/L). Addition of 6.4 g/L Nalco FM-37 to a 2 g/L albumin solution suppressed foaming for approximately 1 h, after which a brief increase in foam height was observed, possible associated with the antifoaming agent. A stable foam height subsequently developed from 10 h and onwards. The presence of gypsum particles (100 g/L) alongside Nalco FM-37 boosts the effect of antifoams, thereby limiting the foam layer to $<2 \times 10^{-2}$ m and prevents the sequence of albumin foam growth and decline observed in the absence of particles.

The two commercial antifoaming agents tested hold a great potential for controlling severe foaming episodes in full-scale plants. However, some limited long-term foaming behavior may arise from the antifoaming agent itself as its formulation and physical properties changes with time.

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Notation

B = Bridge coefficient
d_I = inner diameter, m
E = entry coefficient
H = height, m
S = spreading coefficient
v = velocity, m/s

Greek letters

$\sum$ = Bikerman coefficient, s
δ = Surface tension, mN/m

Subscripts

AW = air/water
i = inner
OW = oil/water
OA = oil/air

Literature Cited

1. Soud H. Developments in FGD. London: IEA Coal Research, 2000.
2. Hoydick M, Brodsky I, Smolenski J. FGD system foaming operational issues and design considerations. Mega Symposium, MD, 2008.
3. Myers D. Surfaces, Interfaces, and Colloids: Principles and Applications. 2nd ed. New York: Wiley VCH Publishers, 1999.
4. Plunkett M. Foams Stabilized by Polymers and Proteins. Stockholm: YKI, 2006.
5. Zheng YJ, Kiil S, Johnsson JE. Experimental investigation of a pilot-scale jet bubbling reactor for wet flue gas desulphurisation. *Chem Eng Sci*. 2003;58(20):4695–4703.
6. Garrett PR. Surfactant Science Series,Vol.45. Defoaming: Theory and Industrial Applications. New York: Taylor & Francis, 1993.
7. Denkov ND. Mechanisms of foam destruction by oil-based antifoams. *Langmuir*. 2004;20(22):9463–9505.
8. Karakashev SI, Grozdanova MV. Foams and antifoams. *Adv Colloid Interface Sci*. 2012;176:1–17.
9. Thiele R, Brettschneider O, Repke JU, Thielert H, Wozny G. Experimental investigations of foaming in a packed tower for sour water stripping. *Ind Eng Chem Res* 2003;42(7):1426–1432.
10. Kister HZ. What caused tower malfunctions in the last 50 years? *Chem Eng Res Des*. 2003;81(A1):5–26.
11. Pugh RJ. Foaming, foam films, antifoaming and defoaming. *Adv Colloid Interface Sci*. 1996;64:67–142.
12. Hansen BB, Kiil S, Johnsson JE, Sonder KB. Foaming in wet flue gas desulfurization plants: the influence of particles, electrolytes, and buffers. *Ind Eng Chem Res*. 2008;47(9):3239–3246.
13. Hutzler S, Lösch D, Carey E, Weaire D, Hloucha M, Stubenrauch C. Evaluation of a steady-state test of foam stability. *Philos Mag*. 2011;91(4):537–552.
14. Alexandersson T. Water reuse in paper mills. Measurements and control problems in biological treatments. Sweden: Lund University, 2003.
15. Brown BP, Brown SR, Senko JM. Microbial communities associated with wet flue gas desulfurization systems. *Front Microbiol*. 2012;3:1–16.
16. Alsaati HA, Ditzler D, Burapatana V, Tanner RD. Using egg albumin foam to extinguish fires. *Braz Arch Biol Technol*. 2003;46(4):735–740.

17. Frandsen JBW, Kiil S, Johnsson JE. Optimisation of a wet FGD pilot plant using fine limestone and organic acids. *Chem Eng Sci*. 2001;56(10):3275–3287.
18. Weast RC, Lide DR. CRC Handbook of Chemistry and Physics, 70th Ed. Boca Raton, FL: CRC Press, 1989–1990;D:146.
19. Kiil S. Experimental and Theoretical Investigations of Wet Flue Gas Desulphurisation. Denmark: Technical University of Denmark, 1998.
20. Hansen BB, Kiil S, Johnsson JE. Investigation of the gypsum quality at three full-scale wet flue gas desulphurisation plants. *Fuel*. 2011;90(10):2965–2973.
21. Brannigan G, Bonfim OFDA. Boundary effects on forced drainage through aqueous foam. *Philos Mag Lett*. 2001;81(3): 197–201.
22. Bikerman JJ. Foams. Vol 80. Springer-Verlag New York, 1973.
23. Hansen BB, Kiil S. Investigation of parameters affecting gypsum dewatering properties in a wet flue gas desulphurization pilot plant. *Ind Eng Chem Res*. 2012;51(30):10100–10107.
24. Kiil S. Drying of latex films and coatings: Reconsidering the fundamental mechanisms. *Progr Org Coatings*. 2006;57(3):236–250.
25. Marinova KG, Basheva ES, Nenova B, et al. Physico-chemical factors controlling the foamability and foam stability of milk proteins: sodium caseinate and whey protein concentrates. *Food Hydrocolloids* 2009;23(7):1864–1876.
26. Mukhopadhyay G, Khanam J, Nanda A. Protein removal from whey waste by foam fractionation in a batch process. *Sep Sci Technol*. 2010;45(9):1331–1339.

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