NOTE

Foam Destruction by Ultrasonic Vibrations

Ultrasonic (US) vibrations prevent formation of foams and promote their destruction, if the vibrating element is placed nearby in the surrounding air. The working distance for rapid foam destruction is 10–15 mm when a sharp vibrating tip is used, but is much larger for a broad tip. Even at greater distances foam is destroyed but the effect needs some time to become noticeable. This agrees with an action of US vibrations through stimulation of squeezing mode surface waves. © 1993 Academic Press, Inc.

INTRODUCTION

Foams occur in many technical situations, frequently as undesirable phenomena. Previous investigations concerning the mechanism of thin film drainage (1–4) suggested that the mechanism of marginal regeneration (5), which is the main effect determining the drainage of vertical thin films, is triggered by squeezing mode surface waves (6) along the vertical film/Plateau border boundaries. If this is true, then it is to be expected that deliberately induced vibrations might accelerate thin film drainage, and thus shorten the life time of foams. The theoretical expectation would run as follows: Vibrations (e.g., ultrasonic ones) are well known to effect surface waves on liquids; in foams, consisting of thin liquid films separating gas bubbles, surface waves in one surface of a film can only persist when they are accompanied by waves in the other surface of the film: some of such cooperating waves will be of the "squeezing" mode type [7] and therefore are expected to enhance film drainage: such accelerated film drainage will lead to films earlier attaining their critical thickness and therefore will destabilize foams.

It might be remarked that vibrations may effect in liquids not only surface waves but also flows. It should be noted, however, that in thin films flows are accompanied in all cases by surface waves, and that influences with regard to wave formation and to flow stimulation therefore cannot be separated. The thin liquid films in a foam are oriented at random with regard to the ultrasonic waves. If the only effect of ultrasonic vibrations would be the induction of liquid motion without systematic connection with surface waves, as much liquid would be transported from the Plateau borders into the films, as out of the films into the borders. However, a systematic connection between surface waves and movement of liquid out of a film into the adjacent borders has been found in the investigations on separate films mentioned (1–6).

The idea of trying to destabilize foams by ultrasonic vibrations is not entirely new. Especially in the patent literature, frequently references to the possibility of foam destruction by application of vibrations, e.g., ultrasonic, can be found (8–15). However, there are also indications of foam generation rather than foam destruction by ultrasonic waves [16]. Recently, it was reported that acoustic waves increase rather than decrease the thickness of thin liquid films [17]. Apparently, the type of effect produced by vibrations depends crucially on frequency and amplitude of the vibrations, and perhaps also on the dimensions of the liquid films in the foam (i.e., on the size of the gas cells), and on the position of the vibrating unit: in the surrounding gas, in the foam itself, or in the liquid from which the foam had been formed.

In view of this conflicting evidence, we thought it worthwhile to test the prediction that thin film drainage may be increased by inducing vibrations, by investigating the influence of ultrasonic vibrations on foam generation and foam destruction. The present paper reports experiments in this respect performed with an easily surveyable apparatus. In order to keep the number of parameters within limits, the frequency was kept constant (20 kHz), but the following parameters were varied: place and type of the ultrasonic vibrating tip; and power of the US vibration. Although the experiments themselves refer to foams rather than to separate films, it will be seen that they enable us to draw the conclusion that not only film rupture is involved in the destroying action of vibrations of foams but that part of the effects reported indicate an influence on film drainage as well.

EXPERIMENTAL MATERIALS

Sodium dodecyl sulfate (SDS): Merck, purity >99%.

Water: twice distilled.

APPARATUS

Foam was generated by introducing nitrogen dried by passage over CaCl_2 , into $35 \times 10^{-6} \text{ m}^3$ of a 0.0025 M SDS solution through a Schott No. D2 porous glass filter. A similar apparatus has been described in Ref. (3). Both the total foam volume, and the volume of the liquid in the foam can be determined from the height of liquid + foam, and the height of the liquid/foam transition. The foam was generated in a thermostated (298 K) measuring tube with inner diameter 29 mm, height 300 mm. The rate of gas inflow was kept constant at $45 \times 10^{-6} \text{ m}^3/\text{min}$ (inflow pressure slightly higher than atmospheric pressure). Ultrasonic vibrations (20 kHz) were generated by a Sonifier S 110 probe; two different tips were employed, with diameters of 3.3 and 12.8 mm, respectively. The power of the US vibrations was adjusted to 27.5, 55, or 110 W. The vibrating tip was located either at a height of 160 mm, or at a height of 260 mm.

A typical experiment consisted of a "dynamic" part and a "static" part [3]; during the former, nitrogen was introduced. The gas flow was switched off at the start of the static part. The transition from the dynamic to the static part took place after 180 s.

RESULTS AND DISCUSSION

Figure 1 shows the total foam volume as a function of time during a typical series of experiments, with the 3.3 mm vibrating tip.

The reference experiment (Exp. 1 in the Fig. 1) is performed in the absence of US vibrations. It is characterized by a rise in total foam volume during the dynamic part and a gradual decay during the static part. With the vibrating tip in the 160 mm position and being active during the dynamic part (Exp. 2), the US vibrations counteract foam generation as soon as the top of the foam comes within 10–15 mm distance of the tip (at a height of 160 mm, the foam volume would be 105.6 cm^3). A similar experiment with the tip at the 260 mm position does not noticeably influence foam generation, since the foam did not reach the 260 mm height (at this height, the foam volume would be 171.7 cm^3). The fact that ultrasonic vibrations counteract foam formation does not agree with random motion induced by the ultrasonic

FIG. 1. Foam volume as a function of time. Gas inflow (dynamic part) during first 180 s. 0.0025 *M* SDS solution in water; breadth of vibrating element 3.3 mm. (+) 1. Reference experiment (no ultrasonic vibration). (Δ) 2. Vibrating element at height 160 mm (corresponding with foam volume 105.5 cm³), start of ultrasonic vibration at the end of gas inflow. (○) 3. As Exp. 2, but with start of US vibrations at the beginning of gas inflow. (+) 4. Vibrating element at height 260 mm (corresponding with foam volume 171 cm³), start of US vibrations at the end of gas inflow. (▲) 5. As Exp. 4, but with start of US vibrations at the beginning of gas inflow.

vibrations in the liquid; it agrees with the theoretical prediction that foam film drainage is enhanced by stimulation of squeezing mode waves in thin films. The only other explanation which appears to be compatible with the observations on the influence of US vibrations on foam formation is, that the vibrations do not affect drainage of films but that they only stimulate squeezing mode vibrations in black films, enhancing film rupture by the Vrij-Overbeek mechanism (7) through increasing the critical film thickness, and thus effecting a decreased life time of the foam. However, this explanation is not easily compatible with the influence of vibrations on a foam after formation.

The evolution of the foam volume during the static part again is affected greatly by the presence of ultrasonic waves, although it is not greatly different for experiments performed with US vibrations present or absent during the foam formation (compare the experiments 2 and 3 of Fig. 1). This agrees with the virtual absence of US vibration influence when the vibrating tip is at a greater distance than 10–15 mm. There still is a pronounced destroying action on foam by the US vibrations even when the tip is at the greater distance, but it takes some time before it becomes apparent. If the US vibrations would act only on the black films, increasing their critical thickness by enhancing squeezing mode surface waves in them, the destroying action on the foam would start simultaneously (though probably at different rates) for both positions of the vibrating tip. The distinct break in the foam volume vs time curve when the vibrating tip is at the greater distance is a strong argument against this possibility.

Thus the combination of the experiments 2–5 from Fig. 1 excludes the possibility that US vibrations affect black films only and confirms the theoretical expectation that the US vibrations at first increase the drainage rate of the thin films in the foam. Only after the drainage has proceeded for some time (about 500 s when the vibrating tip is at the greater distance), does the increased drainage rate result in film rupture to a noticeable degree.

With the apparatus, the liquid content of the foam can be measured as well. It is found that the quantity of liquid incorporated into the foam is not noticeably influenced by the presence of US vibrations. Apparently, although some thin films are ruptured, the liquid released is incorporated in the remaining films rather than passed through to the underlying bulk solution. In itself this is surprising since calculations with the mechanism

FIG. 2. Influence of film thickness on flows (volume per s, per unit length along the border) at a film thickness fluctuation of 2×10^{-7} m, calculated from theory. Equal sized inflow and outflow region. (□) Inflow in inflow region. (+) Outflow in outflow region. (◇) Sum of inflow and outflow.

proposed by one of the present authors (6) lead to the conclusion that at a given amplitude of film thickness fluctuation, film drainage rate is proportional to the third power of the film thickness (see Fig. 2); thus the thick films in the foam are expected to become drained even more rapidly than the thin films. However, before rupture occurs, the thick films will have to reach the thickness of thin films. In the mean time they obtain liquid from rupturing films which were thinner at the start of the experiment; when one of the films meeting at a Plateau border ruptures, the two remaining films combine to form one film containing part of the liquid originally present in the ruptured one.

The influence of US vibrations at a given power consumption is greatly enhanced when a broader tip is used. This is shown in Fig. 3 for the dynamic parts.

FIG. 3. Experiment 3. Influence of US vibration power on foam volume during gas inflow; US vibrations starting at the beginning of gas inflow. (●) Reference experiment (no US vibrations). (○) 55 W, vibrating element 3.3 mm. (Δ) 27.5 W, vibrating element 12.8 mm. (+) 55 W, vibrating element 12.8 mm.

FIG. 4. Influence of US vibration power on destruction of foam after formation. Vibrating element 12.8 mm, start of US vibrations at the end of gas inflow. (●) Reference experiment. (○) 27.5 W. (+) 55 W. (Δ) 110 W.

Figure 4 shows, for the static parts of the experiments, the influence of increasing power of the US vibrations. In these experiments, US vibrations were started only at the beginning of the static part. From the data available at present it is not yet quite clear whether this influence can be described by a linear relation, or whether a quadratic term should be included. For a linear dependence, a best fit would be:

$$\frac{dV_{\text{foam}}}{dt} = a + b \cdot p$$

with V_{foam} = total volume of the foam (m^3); t = time (s); p = power (W); $a = 4.49 \times 10^{-9} \text{ m}^3/\text{s}$; $b = 6.15 \times 10^{-10} \text{ m}^3/(\text{W} \cdot \text{s})$; but this relation is rather strongly dependent on the geometry of the apparatus.

It is seen that, although a complete understanding of the quantitative connection between foam lamella thickness, size and wave parameters must be postponed until data are available on the influence of US vibrations on separate films, theory nevertheless supplies important insights into the processes occurring during foam destruction.

SUMMARY

Ultrasonic vibrations (20 kHz) can be employed for effectively destroying foam. Especially when a rather broad vibrating tip is used, and when the vibrating tip is at a small distance from the foam in the surrounding air, foam destruction can be achieved with rather low power consumption. The

fact that film formation and persistence is counteracted by US vibrations agrees with the following theoretical train of thoughts:

- (a) vibrations effect surface waves on liquids;
- (b) in foams, consisting of thin liquid films separating gas bubbles, surface waves in one surface of a film can only persist when they are accompanied by waves in the other surface of the film;
- (c) part of such cooperating waves will be of the "squeezing" mode type and therefore are expected to enhance film drainage;
- (d) accelerated film drainage will lead to films earlier attaining their critical thickness and therefore destabilize foams.

ACKNOWLEDGMENT

The authors want to express thanks to DSM Research (Geleen/The Netherlands) for financial support.

REFERENCES

- Hudales, J. B. M., and Stein, H. N., *J. Colloid Interface Sci.* **137**, 512 (1990).
- Hudales, J. B. M., and Stein, H. N., *J. Colloid Interface Sci.* **138**, 354 (1990).
- Hudales, J. B. M., and Stein, H. N., *J. Colloid Interface Sci.* **140**, 307 (1990).
- Stein, H. N., in "Directional Characteristics of Marginal Regeneration" (K. L. Mittal and D. O. Shah, Eds.), Surfactants in Solution, Volume 11, p. 481. Plenum, New York/London, 1991.
- Mysels, K. J., Shinoda, K., and Frankel, S., "Soap Films: Studies of their Thinning and a Bibliography." Pergamon, Elmsford, NY, 1959.
- Stein, H. N., *Adv. Colloid Interface Sci.* **34**, 175 (1991).
- Vrij, A., and Overbeek, J. Th. G., *J. Amer. Chem. Soc.* **90**, 3074 (1968).
- Fuji Photo Film Co., Ltd. Jpn. Kokai Tokkyo Koho 57006365, 4.2.1982.
- Chendke, P. K., and Fogler, H. S., *Chem. Eng. J.* **8**, 165 (1974).
- Varlamov, V. G., and Zaikina, V. V., *Kompleksn. Ispol'z. Miner. Syr'ya* **11**, 83 (1988).
- Shin-Etsu Chemical Ind. Co., Ltd., Jpn. Kokai Tokkyo Koho 56137938, 28.10.1981.
- Fuji Photo Film Co., Ltd., Jpn. Tokkyo Koho JP 55006405, 16.2.1980.
- Hay, B., and Shapland, D. G., *Engl. Pat. No. 1 354 678*, 18.8.1970.
- Karpovich, J., U.S. Patent No. 3,290,256, 6.12.1966.
- Isayev, A. S., and Mandelbaum, S., *Polym. Eng. and Sci.* **31**, 1051 (1991).
- Park, H., and Youn, J. R., *J. Eng. Indust.* **114**, 323 (1992).
- Zamashchikov, V. V., and Kakutkina, N. A., *Kolloidn. Zh.* **54**, 64 (1992). [English translation, p. 192]

N. SANDOR AND H. N. STEIN¹

Laboratory of Colloid Chemistry, Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands

Received March 3, 1993; accepted July 1, 1993

¹ To whom correspondence should be addressed.