Stability of Cellular Foam Generated from Amphoteric Surfactant Aqueous Solution

Kae Fujita, Tamiya Kishimoto[1], Kazutaka Nagao[2] and Toshiro Miyahara[3*]

Department of System Science, Graduate School of Engineering, Okayama University of Science
1-1, Ridai-cho, Okayama 700-0005, Japan
[1]Department of Life Science, Faculty of Science, Okayama University of Science
1-1, Ridai-cho, Okayama 700-0005, Japan
[2]Research Institute of Technology, Okayama University of Science
1-1, Ridai-cho, Okayama 700-0005, Japan
[3]Department of Applied Chemistry, Faculty of Engineering, Okayama University of Science
1-1, Ridai-cho, Okayama 700-0005, Japan

Experiments were carried out to investigate the stability of cellular foam generated from an amphoteric surfactant aqueous solution in a standard bubble column. A typical growth and collapse process were found, and the cellular foam became stable with increasing pH of the solution under both acidic and basic conditions. The critical film thickness calculated from the thinning equation, the well-known Reynolds equation, was between 100 to 400 nm. Of particular note is that the cellular foam was not observed at pH=7 of the liquid.

1. Introduction

Foam is a system of bubbles dispersed in a liquid and stabilized by surfactant adsorbed at the gas/liquid interfaces. Such foam appears in chemical reactors or bioreactors, and leakage causes serious environmental pollution. Therefore, it is necessary to examine foam breakage in reactors. Generally, two types of foam exist: dispersed bubbles and packed bubbles. The latter, called cellular foam, is a target for foam breakage and shows a gas holdup greater than 90%. The effect of physical properties or operating conditions on

---

*E-mail: miyahara@dac.ous.ac.jp

cellular foams have been discussed by several authors but no one has yet published satisfactory data for predicting the important dispersion characteristics, such as foam height and film thickness from a knowledge of the physical properties of the fluids, bubble size and gas velocity. It is recognized that the cellular foam has a structure composed of dodecahedral bubbles, as shown by Hartland and Barber.[1] They proposed a uniform film model of film drainage in the Plateau border to describe the rate of thinning of a film in terms of the physical properties of the liquid, the film dimension and the force exerted on the film.

In the present study, the stability of cellular foam formed from an amphoteric surfactant (n-dodecyldimethyl (3-sulfopropyl) ammonium hydroxide) aqueous solution in a standard bubble column with a perforated plate was examined by observing the cellular foam height and considering the critical film thickness between bubbles using the thinning equation of liquid proposed by Hartland and Barber [1] and Barber and Hartland.[2] As a result, a typical growth and collapse process were found. The critical film thickness obtained decreased with the pH of the liquid under both acidic and basic conditions. Furthermore, of particular note is that the cellular foam was not observed at pH=7 of the liquid.

2.   Experimental

The liquid used for the experiment was composed of n-dodecyldimethyl (3-sulforpropyl) ammonium hydroxide (amphoteric surfactant) and distilled water. This surfactant solution works as a cationic surfactant under acidic conditions and an anionic one under basic conditions. The concentration of this surfactant was tenfold that of the critical micelle concentration (CMC); 3.0 mol/m^3 for this surfactant), on the basis of the preliminary test described in our previous paper.[3]

The Wilhelmy method was used to measure the surface tension of the liquid. A rotational viscometer was used to determine the viscosity, a density meter for the density and a surface viscosity meter for the surface viscosity. The values are given in Table 1.

A column was designed and constructed to produce cellular foam under controlled conditions and is illustrated in Fig. 1. The liquid and cellular foam were contained in a vertical Plexiglas pipe of 10 cm internal diameter and surrounded by a water jacket, through which water from a thermostatted tank was circulated. Air was passed into the liquid through a perforated plate with 84 holes, each of 0.5 mm diameter, to form cellular foam. The

Table 1
Physical properties of amphoteric surfactant aqueous solutions.

| pH	Temp. [K]	Density [kg/m^3]	Viscosity [Pa•s]	Surface tension [N/m]	Surface viscosity [kg/s]
4.0	293–308	1003–1008	0.000793–0.00103	0.0328–0.0377	0.000118–0.000132
5.0	293–308	1003–1008	0.000774–0.00105	0.0381–0.0389	0.000083–0.000129
6.0	293–308	998.1–1003	0.000809–0.00106	0.0367–0.0390	0.000108–0.000133
8.0	293–308	995.4–1003	0.000707–0.00105	0.0373–0.0392	0.000114–0.000130
9.0	293–308	1002–1007	0.000801–0.00108	0.0381–0.0387	0.000116–0.000124
10.0	293–308	998.2–1003	0.000782–0.00104	0.0339–0.0389	0.000114–0.000134
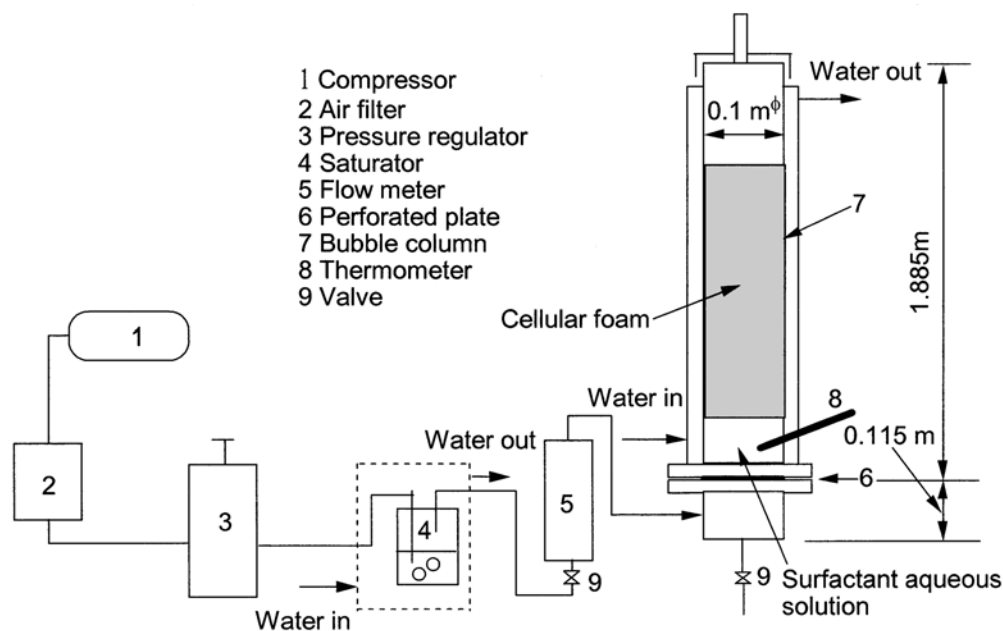
Fig. 1.   Experimental apparatus.

superficial gas velocity employed in this study was varied in the range of $2.12 \times 10^{-3} - 2.12 \times 10^{-2}$ m/s.

In order to avoid heat and mass transfer effects, care was taken to ensure that the gas was in equilibrium with the liqui; that is, air was passed through a wash bottle containing water immediately before the column. Furthermore, to avoid, as much as possible, the effect of vaporization and disturbance, a cap with a pipe was placed at the column top. Cellular foam height was measured by visual observation.

It is very difficult to measure the bubble size in cellular foam. To this end, we used the correlation equations proposed by Miyahara *et al.*[4]

3.   Results and Discussion

Figure 2(a) shows the results for cellular foam height at a given gas velocity (U_{gc}=0.00425 m/s) and pH of the liquid (pH=9) as a function of time. From this figure, the cellular foam height was shown to increase, reaching a maximum and then decreasing with time. The maximum value decreased with the liquid temperature, probably due to the decrease in liquid viscosity. The effect of the pH of the liquid on cellular foam height is illustrated in Fig. 2 (b). The trend of growth of the cellular foam with time is similar to that shown in Fig. 2 (a). From this figure, it is seen that the cellular foam height increased with pH under both basic and acidic conditions, and, broadly speaking, the cellular foam became stable under basic conditions. Previously, the authors[5] examined the behavior of cellular foam generated from ionic surfactant aqueous solutions and found that the cellular foam of anionic surfactant
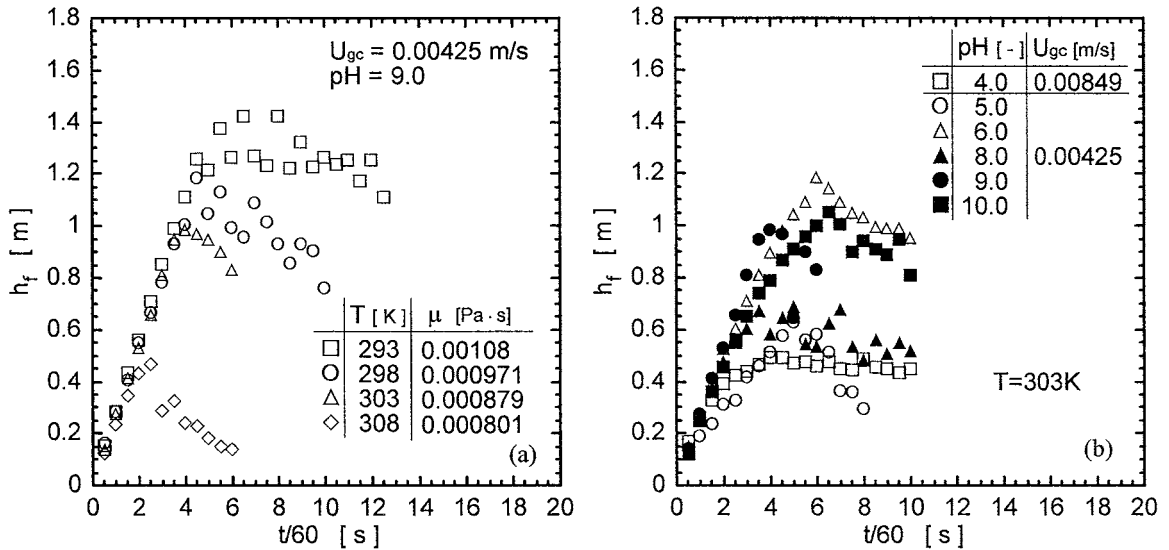
Fig. 2.   Growth of cellular foam.

aqueous solutions is stable compared with that of cationic surfactant aqueous solutions. Therefore, the stability observed under basic conditions in this study is probably a consequence of the result mentioned above. Here, of particular note is that the cellular foam was not observed at pH=7 of the liquid. Although the stability of the cellular foam seems to be connected with the pH of the liquid, we could not find the precise relationship between them.

Figure 3 shows the behavior of the collapse of cellular foams, corresponding to that of the growth shown in Fig. 2. The values of the vertical axis at zero time are initial foam heights at given superficial gas velocities. From Fig. 3 (a), it can be seen that the cellular foam height decreased linearly with time. A similar trend is found in Fig. 3 (b), showing the effect of the pH of the liquid. From this figure, it can be observed that the cellular foam is stable at a lower temperature and a higher pH of the liquid.

Thus, to evaluate the stability of the cellular foam, we used the following thinning equation of liquid, the well-known Reynolds equation, employed by Hartland and Barber [1] and Barber and Hartland:[2]

$$-\frac{d\delta}{dt} = \frac{8F\delta^3}{3n^2\pi\mu R^4},$$ (1)

where $F/(\mu R^2)$ is the pressure acting on the film (that is, capillary pressure minus disjoining pressure),[6] δ is the film thickness at time t, μ is the liquid viscosity and n is the number of immobile film surfaces. However, we neglected the disjoining pressure in this case, because
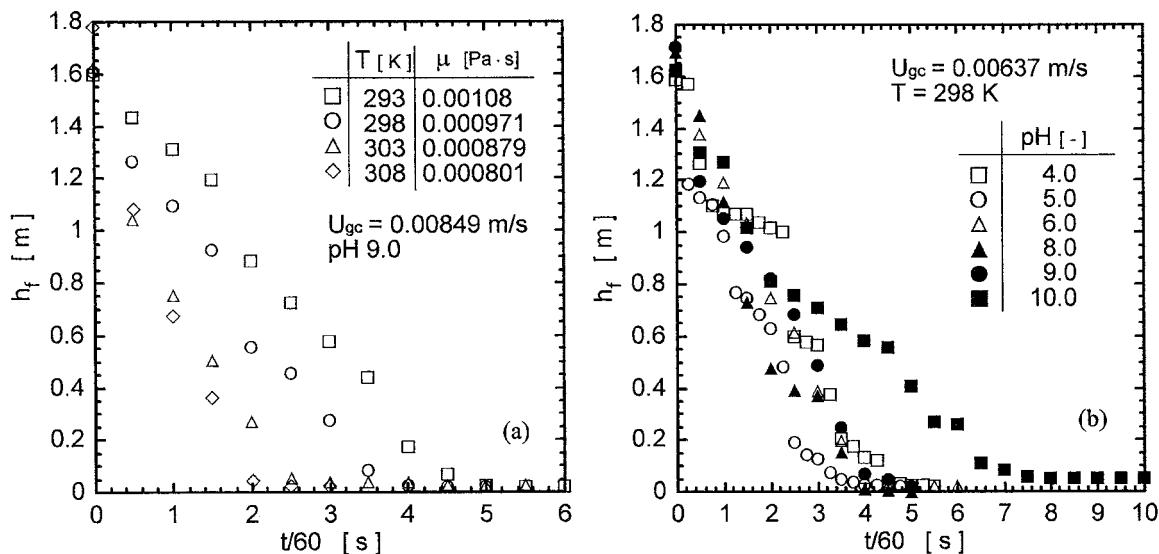
Fig. 3.   Collapse of cellular foam.

the capillary pressure is greater than the disjoining pressure by about tenfold.[5] Assuming that *n*=2 due to the tenfold concentration of CMC and that the drainage of the films may be represented by the axisymmetric drainage of liquid from between two flat plate discs of radius *R*, the following equations can be obtained

$$\delta_c = \frac{0.71 \left(U_{gc}\mu \right)^{5/7} d_b^{9/7}}{\left(\rho g \right)^{1/7} \left(\sigma h_{fc} \right)^{4/7}} \text{ for growth} \tag{2}$$

$$\delta_c = \frac{0.65 d_b^{9/7} h_0^{1/7} \mu^{5/7}}{\left(\rho g \right)^{1/7} \sigma^{4/7} t^{5/7}} \left[\left(\frac{h_f}{h_0} \right)^{-1/7} - \frac{h_f}{h_0} \right]^{5/7} \text{ for collapse} \tag{3}$$

as proposed by Hartland and Barber [1] and Barber and Hartland.[2] The critical film thickness for growth and collapse of cellular foam can be obtained by substituting the maximum foam height into eq. (2) and the foam height at a given time into eq. (3), respectively.

   Figure 4 shows the critical film thickness, including those for the growth and collapse, as a function of superficial gas velocity. For comparison, we also show the results for nonionic, anionic and cationic surfactant aqueous solutions.[3,5] From this figure, the critical film thickness appears to be between 100 and 400 nm, which is slightly larger than that for nonionic sufactant aqueous solutions.[3] Furthermore, it can be seen that the critical film thickness decreases with pH, corresponding to the result of the foam height shown in Figs. 2 and 3.
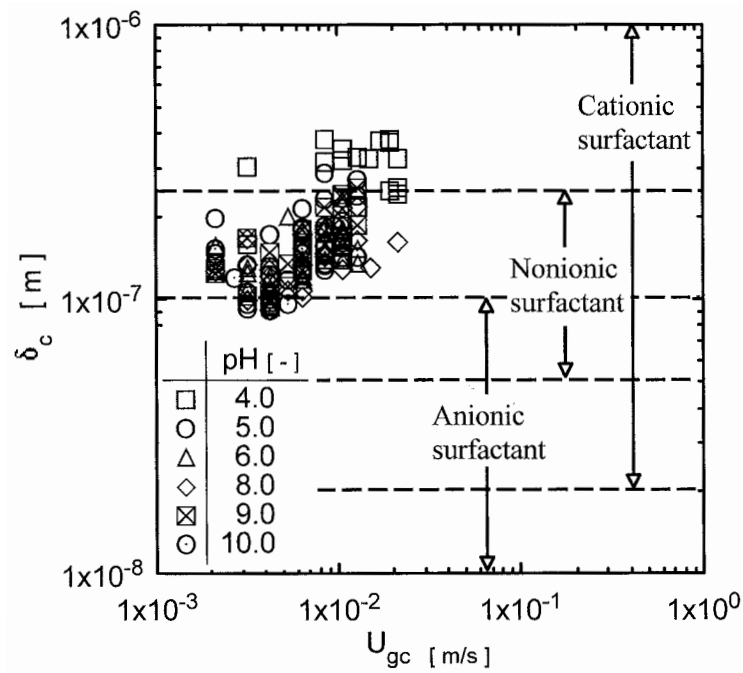
Fig. 4.   Critical film thickness.

4.   Concluding Remarks

To clarify the stability of the cellular foam formed from an amphoteric surfactant aqueous solution, experiments were performed using n-dodecyldimethyl (3-sulforpropyl) ammonium hydroxide as a surfactant. As a result, the following conclusions were drawn:
(1) The cellular foam height increases, reaches a maximum and decreases with time for the growth and becomes stable with increasing pH of the liquid. Of particular note is that the cellular foam was not observed at pH=7.
(2) The critical film thickness appears to be between 100 and 400 nm.

5.   Notation

d_b =   volumetric mean bubble diameter, m
F =   force exerted on film, N
g =   gravitational acceleration, m/s^2
h_f =   cellular foam height, m
h_{fc} =   cellular foam height at the rupture of lamella, m
h_0 =   initial foam height, m

n = number of immobile film surfaces
R = radius of circular film having the same area as the face of a dodecahedron, m
r = radius of curvature of walls of Plateau border, m
T = temperature, K
t = time, s
U_{gc}= superficial gas velocity, m/s
δ = film thickness, m
δ_c = critical film thickness, m
μ = viscosity, Pa.s
ρ = density, kg/m^3
σ = surface tension, N/m

References

1 Hartland, S. and Barber A.D. (1974): A model for cellular foam. *Trans. Instn. Chem. Engrs.* **52**: 43–52.

2 Barber, A.D. and Hartland S. (1975): The collapse of cellular foam. *Trans. Instn. Chem. Engrs.* **53**: 106–111.

3 Fujita, K. and Miyahara, T. (2005): Stability of cellular foam formed from nonionic surfactant aqueous solution. *Kagaku Kogaku Ronbunshu* **31**: 7–14.

4 Miyahara, T., Matsuba, Y. and Takahashi, T. (1982): Size of bubbles generated from perforated plate. *Kagaku Kogaku Ronbunshu* **8**: 13–17.

5 Fujita, K. and Miyahara, T. (2006): Stability of cellular foam formed from anionic and cationic surfactant aqueous solution. *Kagaku Kogaku Ronbunshu* **32**: 103–114.

6 Manev, E.D., Sazdanova, S.V. and Wasan, D.T. (1984): Emulsion and foam stability — The effect of film size on film drainage. *J. Colloid and Interface Science* **97**: 591–594.