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Foam Fractionation of Particles in Low Gravity

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Foam fractionation of heavy particles has been obtained aboard an aircraft that provides a low-gravity environment by flying parabolic trajectories. Results for large silica, glass, and steel pellets (>0.2 mm) show that, using minimally supporting froths, both mass transport and separation are possible. For single-pass batch separations in low gravity, concentration factors reached threefold (compared with a ninefold theoretical limit and no separation in unit gravity). The impact of reduced gravity is discussed for splitting large particle sizes from low surfactant fluids; possible interest includes bubbling premium biologicals (whole cells, proteins, and viruses, etc.) from native solutions without surfactant addition or membrane disruption.

Nomenclature

R = average particle radius
R_B = average bubble radius
$R_{\max,g}$ = maximum radius for particles at unit gravity
V = bubble velocities
$\Delta N/N$ = probability of particle entrainment and floatation
κ = Schledko's material constant for particle-bubble interactions
ρ = particle density
σ = foam surface tension
Φ = wetting angle

Introduction

FOAM floatation refers to the removal of suspended matter from a liquid phase by adsorption onto foam. Powdered carbon and various inorganic colloids have been bubbled off, [1–3] as well as biologicals, including algae,[4] a virus,[5] and bacteria.[6] In analytical work, foams have proven useful for trace analysis of metals, radioactive waste treatment, and ore floatation.[4] The experiments described here represent a preliminary examination of the possibilities of foam floatation in low gravity.

Previous work has examined gravitational effects on foams. For vertically misaligned columns, a 1-deg angular tilt from the gravity vector leads to "pronounced effects on surfactant concentration" along the column length, with back circulation and fluid channeling.[7] In reduced gravity, a number of investigators have examined froth production,[8] chemical reaction on foams,[9,10] and metallic foaming.[11–13] In addition to gravity, other body forces such as magnetic fields[14] show a pronounced effect on bubbling of ionic metals such as Ni, Co, and Cu.

Gravity affects foam floatation in several ways; gravity 1) limits floatable particle sizes,[15] 2) leads to bubble coalescence from film drainage,[16–19] 3) increases surfactant requirements,[4] and 4) increases bubble-particle collision velocities.[15] Gravity sets an upper limit on particle sizes that can be adsorbed effectively on bubble surfaces. For large particle sizes adhered on bubbles, Scheldko et al.[15] derived a theoretical limit that scales as the inverse one-half power of gravity; an order of magnitude increase in particle size is predicted for each two order of magnitude reduction in effective gravity. Gravity also leads to film drainage and thinning of bubbles, such that coalescence reduces available surface area for particle attachment.[17] In addition, to remove a given solute, low-gravity reductions in particle weight can minimize the required surfactant quantities.[4] Compared with other separation techniques, one disadvantage of terrestrial foam floatation generally is its high surfactant requirements (stoichiometric or greater). Although these high surfactant levels add to cost, the more important problem of interest here is the disruptive effect of detergents on sensitive biologicals. Finally, gravity determines the bubble rise rate for impacting suspended particles and hence fixes the collision velocity for the three-phase system.[15] For these reasons, careful consideration should be given to gravity effects in foam floatation of suspended particulates, with particular attention paid to advantages and disadvantages of low-gravity processing.

Materials and Methods

Low gravity was achieved using an airplane flying parabolic trajectories. The plane is a NASA-modified KC-135 turbojet that alternately achieves 30 s of high and low gravity. The quality of low gravity was measured using onboard accelerometers to be 1/100 Earth gravity (9.8 cm s^{-2}) with a random component, $\pm 0.002\ g$.

Three materials were used for sample tests: stainless steel cut wire shot (R=0.0584 cm), uncoated glass beads (R=0.04 cm), and silica sand (0.035<R<0.041 cm). Volumes of the particulate suspension (50 ml) were foamed in a Plexiglas apparatus (Fig. 1), consisting of a vertical-sided tube 12 cm long and 1.3 cm in diameter. A sidearm served as feed source for an air pump (maximum 10 ml s^{-1}), and excess gas was vented from a raised exit port. Solids from the product stream (foamate) were sampled at the conclusion of a low-gravity batch run without introducing a foam-collapsing agent. All experiments were conducted using a foaming suspension of 50 ml deionized (DI) water, 1 ml glycerine, and 5 ml of a commercial liquid detergent. Results were found to be recipe independent for several detergent types and concentrations between 1 and 10% (by volume). Each test was performed between 26–28°C. The gas foaming rate was adjusted to the highest level, which avoided liquid entrainment of feed material.

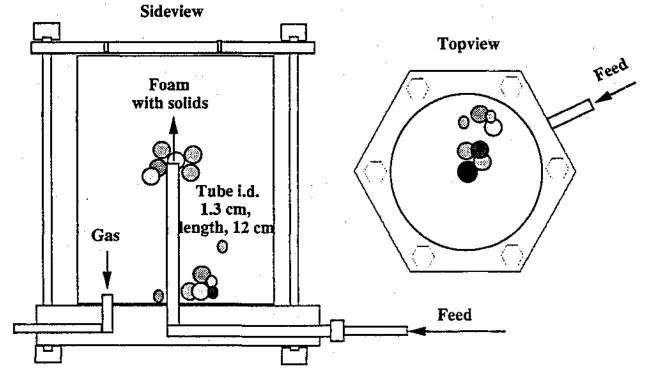

Fig. 1 Schematic diagram of foam fractionator, top and side view.

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Foam Floatation Theory

The theory of foam floatation and particle-bubble collisions is a well-established field with numerous reviews and books. Notably, Schledko et al.[15] have derived theoretical limits on particle size for foam fractionation,

$$R_{\max, g} = \sin\frac{\phi}{2}\sqrt{\frac{3\sigma}{2\rho g}} \tag{1a}$$

Equation (1) is used to compute the gravity dependence of floatable sizes for particles of different wetting angles and densities (Figs. 2 and 3). Taking typical values[15] for glass bubbled in unit gravity (980 cm s^{-2}) gives a maximum particle size of 0.48 mm ($\rho \sim 1$ g cm^{-3}, $\sigma \sim 50$ dyne cm^{-1}, $20 < \phi < 40$ deg). In practice, the observed upper limit on particle size range is considerably lower than this. Normally, terrestrial floatation is not effective for large particles, $R > 0.1$ mm. The experimental upper limit[15] is estimated to lie between 0.15 and 0.30 mm for heavier materials and between 0.5 and 2 mm for lighter ones (e.g., coal and sulphur). For a relative density of 3 g cm^{-3} (compared with steel beads, 3.59), the upper experimental limit has been estimated at 0.2 mm. These results are consistent with the present experiments performed in unit gravity, where floatation was not achievable for large particles (>0.3 mm) of any material. Low-gravity processing, on the other hand, yielded solid splits of large particles with recovery efficiencies up to 42%.

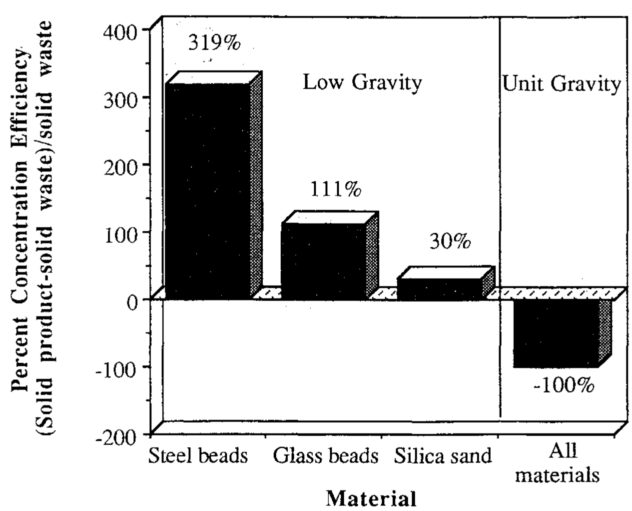

Fig. 2 Gravitational limits on maximum floatable particle size as a function of wetting angle.

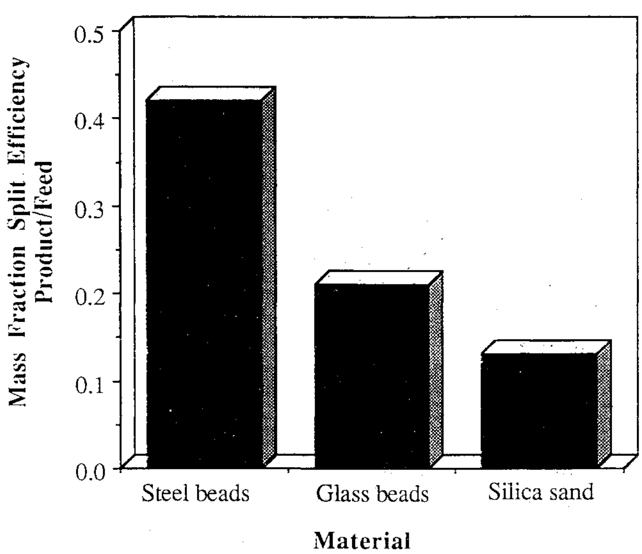

Fig. 3 Gravitational limits on maximum floatable particle size as a function of particle density.

Table 1 Concentration factors and recoveries of particles by foam floatation in low gravity (9.8 cm s^{-2}), gas volume 300 ml, product foamate volume 5 ml, mean bubble diameter 0.8 cm

Material, g/ml density	Particles in product, g	Concentration factor	Solids recovered, %
Steel beads, 4.59	4.43	3.19	42
Glass beads, 1.775	2.35	1.11	21
Sand, 1.705	0.41	0.30	13

It is worth noting that since these yields have not been optimized for either the particular three-phase systems or the gas flow rates, prospects for recovery should improve with further work. For example, the bubbles produced by this method were few and large (0.8 cm) compared with typical floatation conditions (average radii, $R_B = 50.45$ mm with 80% of the bubbles within 0.25 and 0.6 mm radii). For different bubble radii R_B, Derjaguin and Dukhin calculated the entrainment probability of small particles $\Delta N/N$ by the current flowing around a moving bubble as

$$\frac{\Delta N}{N} = \frac{R}{R_B} \tag{2}$$

Hence, from Eq. (2), recovery rates observed here are an order of magnitude below what would be expected from optimized bubbling conditions. Accompanying increases in the number of bubbles (e.g., using an efficient bubble generator), the low-gravity concentration factors would be expected to approach their maximum theoretical limits.

For low-gravity processing, several suspensions are worth examining in more detail. For example, consider the expanded region for particle sizes that can be floated in low gravity compared with unit gravity. The lower limit for particle radii shown in Fig. 3 is adapted from Schledko et al.[15] and results from wetting conditions,

$$R_{\min} < \frac{3\kappa^2}{V^2\rho\sigma(1-\cos\Phi)} \tag{3}$$

(for typical values of bubble velocities $V = 20$ cm s^{-1}, particle density $\rho = 3$ g cm^{-3}, surface tension $\sigma = 50$ dyne cm^{-1}, and material constant $\kappa = 2.8\times10^{-5}$).

Results and Discussion

Table 1 shows the results of three low-gravity experiments. Overall, the mean number of particles adsorbed per ml of feed foam was large and valued at approximately 10^3 particles ml^{-1}. These compare with zero solids recovery achievable in product streams using the same apparatus but in unit gravity. Based on the weight of solids in the product and waste streams, the floatation efficiency can be determined from the final concentration factor: ($C_{\text{product}} - C_{\text{waste}}/C_{\text{waste}}$). From the experimental conditions in the original feed solution and large particle sizes (R>0.035 cm), the maximum possible concentration factor was ninefold. Results in unit gravity show no solids concentration in the product stream ($C_{\text{product}} - C_{\text{waste}}/C_{\text{waste}}) = -1$, whereas in low gravity the equivalent values ranged between 0.3 and 3.19. The highest floatation was found for steel beeds of high density and small particle sizes. As measured by both particle number and total mass separated, the descending order of concentration efficiency was as follows: stainless steel > glass > silica sand. Future work will characterize surface properties comprehensively and correlate wetting behavior to observed splits. In Figs. 4 and 5, concentration factors and equivalent mass recovery percentages (particle mass in product/particle mass in original feed) are compared between unit and low gravity. As indicated, no separation was observed in unit gravity for any of the particle sizes and materials tested, whereas up to 42% of feed particles could be effectively adsorbed and floated on froth membranes in low gravity.

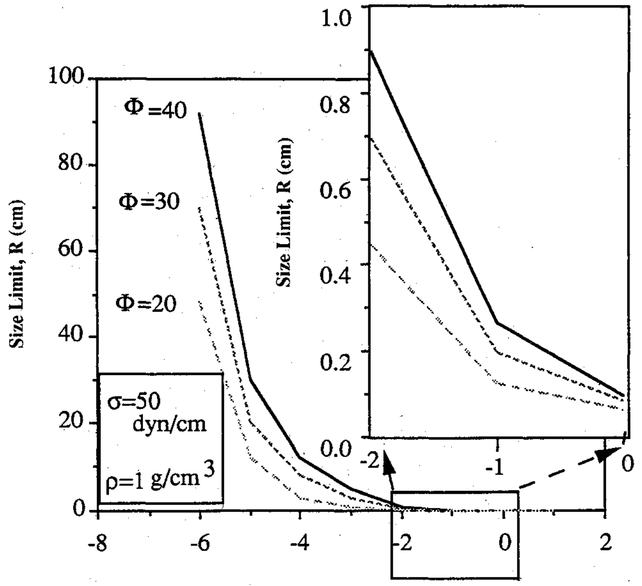

Fig. 4 Experimental concentration efficiency for test materials: stainless steel, glass, and silica sand.

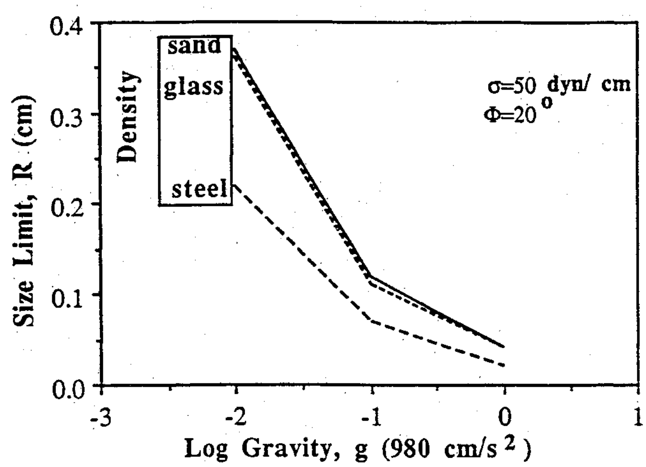

Fig. 5 Mass fraction recovery rates for test materials—stainless steel, glass, and silica sand—compared with a maximum possible recovery of 100%.

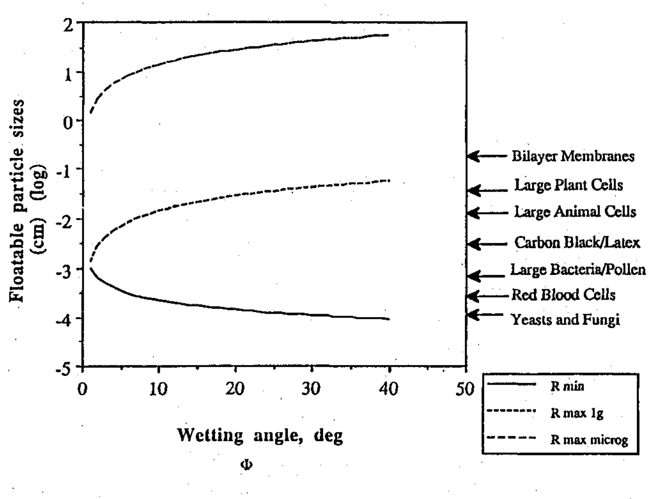

Fig. 6 Theoretical upper and lower bounds on floatable particle sizes for different wetting angles.

Equation (1) was used to calculate the gravitational limits on floatability as a function of wetting angle. The maximum particle radii that can be bubbled off are compared with typical particle sizes for biological materials of interest in Fig. 6. The top line corresponds to microgravity fractionation compared with the central dotted line for unit gravity fractionation. Typical particle sizes for biological materials are shown on the right.

Several biological and metallurgical examples of possible foam separations warrant future consideration. For instance, Gaudin et al.[5] could not float *E. coli* bacteria in unit gravity unless 5% sodium salt solutions were added. The successful 100% recovery of salted froths, however, was found to "alter the morphology of bacteria" and also to concentrate the froth tailings with large amounts of salt. Such ionic salts and their frothing power would be less critical for low-gravity processing, and hence separations may be achievable in growth media alone. Similar effects of high osmolarity on more delicate cells (e.g., red blood cells) precludes salt as an aid to float other large biologicals. Finally, low-gravity foaming behavior with particle separations bears on adjunct processes such as metallic foam formation with matrix particles.[11–13,16]

Concluding Remarks

The study of low-gravity floatation of suspended particulates has shown that significantly larger particles can be supported stably on foam membranes and hence that larger total solids transport can be achieved. These experimental results are consistent with the conclusion that low gravity offers a unique test of foam floatation. Larger floated particles and smaller quantities of surfactant follow as outcomes of low-gravity processing. Separations of large particles, either in native solutions or without surfactants, may hold some promise for well-defined process engineering. Separating premium biologicals (whole cells, proteins, and enzymes, etc.) is a good candidate, particularly those biological materials that are sensitive to membrane disruption or conformational changes on treatment with surfactants. In addition, proposed waste treatment on long-duration space missions may integrate several components of algal treatment, separation of waste components, and recycling of purified streams for closed systems.[18] In this regard, low-gravity tests can validate conceptual issues, including bubble flows in the absence of buoyancy and particle holdup on wetted boundaries within feed streams. As part of an interplanetary probe for exobiological searching, foam fractionation was previously proposed for the concentration of any nonmineral, biological components taken from soil augers.[19]

References

[1]Grieves, R. B., Bhattacharyya, D., and Crandall, C. J., "Foam Separation of Colloidal Particulates," *Journal of Applied Chemistry,* Vol. 17, No. 3, 1967, pp. 163–174.

[2]Grieves, R. B., and Bhattacharyya, D., "Foam Separation of Colloidal Particles: Rate Studies," *Journal of Applied Chemistry,* Vol. 18, No. 7, 1968, pp. 149–158.

[3]Grieves, R. B., and Chouinard, E. F., "Foam Separation of Active Carbon," *Journal of Applied Chemistry,* Vol. 19 , No. 4, 1969, pp. 60–71.

[4]Clarke, A., and Wilson, D. J., *Foam Floatation: Theory and Applications,* Marcel Dekker, New York, 1983.

[5]Gaudin, A. M., Davis, N. S., and Bangs, S. E., "Floatation of *Escherichia coli* with Sodium Chloride," *Biotechnology and Bioengineering,* Vol. 4, No. 5, 1962, pp. 211–220.

[6]Morrow, A. W., "Concentration of the Virus of Foot and Mouth Disease by Foam Floatation," *Nature,* Vol. 222, No. 9, 1969, pp. 489, 490.

[7]Valdes-Krieg, E., King, C. J., and Septon, H. G., "Effect of Vertical Alignment on the Performance of Bubble and Foam Fractionation Columns," *AIChE Journal,* Vol. 21, No. 14, 1975, pp. 400–402.

[8]Wessling, F. C., McManus, S. P., Matthews, J., and Patel, D., "Foam Formation in Low-Gravity," *Journal of Spacecraft and Rockets,* Vol. 27, No. 8, 1990, pp. 324–334.

[9]Grodzka, P. G., and Bourgeois, S. V., "Chemical Reactions in Low-*G*," AIAA Paper 78-166, Jan. 1978.

[10]Naumann, R. J., and Mason, E. D., "Summaries of Early Materials Processing in Space Experiments," NASA TM-78240, Aug. 1979.

[11]Patten, J. W., and Greenwell, E. N., "Closed Cell Foams Produced from Sputter Deposited Aluminum—Experiments in Earth and Space," AIAA Paper 77-193, Jan. 1977.

[12]Pond, P. B., and Winter, J. M., "SPAR IX Postflight Engineering Report," *Space Processing Applications Rocket Project (SPAR) SPAR IX Final Report,* edited by R. Poorman, NASA TM-82549, Jan. 1984, pp. 14–19.

[13]Schaumlautfer, W., "TEXUS 5 Experiment: Metallschaumherstellungen," Dornier System, Final Rept. No. 5, Dusseldorf, Germany, Aug. 1982.

[14]Skrylev, L. D., and Trigubenko, T. Z., "Magnetic Field Effects on Foam Floatation of Metallic Ions," *Zhurnal Prikladnoi Khim.,*Vol. 49, No. 18, 1976, pp. 1629–1635.

[15]Scheldko, A., Toshev, B. V., and Bojadjiev, D. T., "Attachment of Particles to a Liquid Surface," *Journal of the Chemical Society Faraday Transactions,* Vol. I72, No. 16, 1976, pp. 2815–2825.

[16]Hudales, J. B. M., and Stein, H. N., "The Influence of Solid Particles on Foam and Fluid Drainage," *Journal of the Colloid Interfac. Science,* Vol. 140, No. 3, 1990, pp. 307–320.

[17]Steiner, L., Hunkeler, R., and Hartland, S., "Behaviour of Dynamic Cellular Foams," *Transactions of the Institute of Chemical Engineers,* Vol. 55, No. 8, 1977, pp. 153–163.

[18]Pol, E., Banks, G., and Luttges, M., "Thirty Second Duration of Low-Gravity Exposure and Euglena Motility," *American Society for Gravitational and Space Biology Bulletin,* Vol. 3, No. 5, 1989, p. 85.

[19]Lederberg, J., "Exobiology, Experimental Approaches to Life Beyond the Earth," *Space Research,* edited by H. Kallman Bijl, North Holland, Amsterdam, 1960, pp. 1165–1178.

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