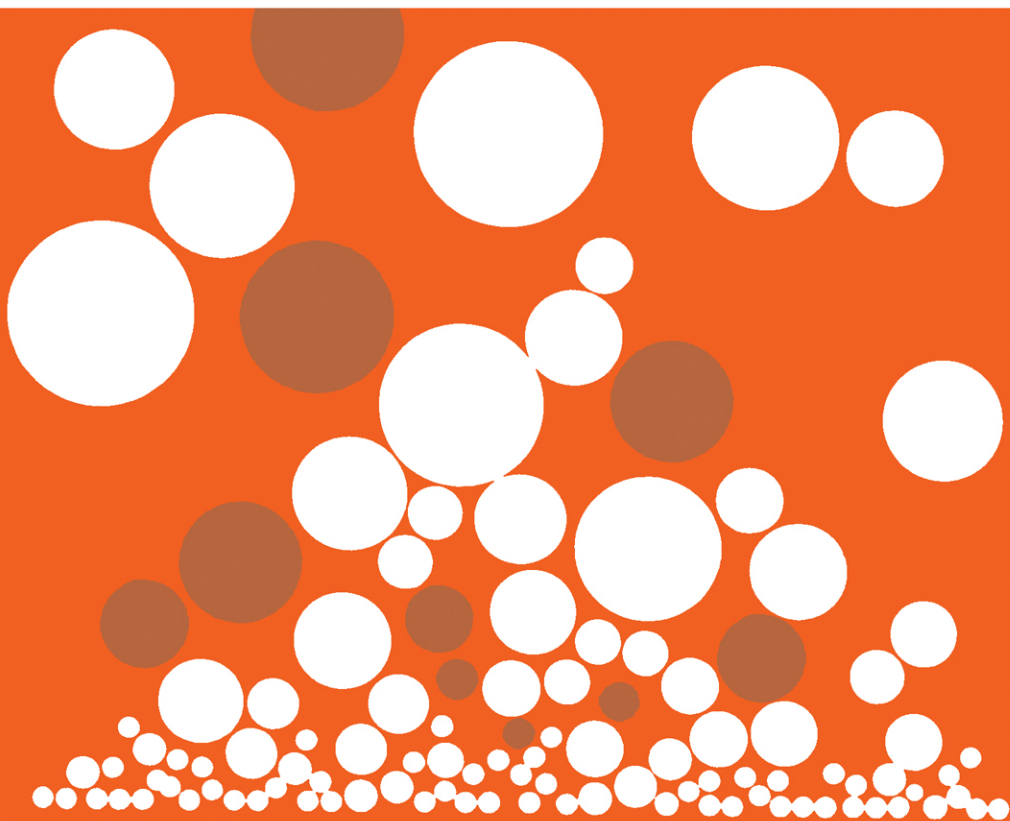


adsorptive bubble separation techniques

EDITED BY **ROBERT LEMLICH**



ACADEMIC PRESS

**adsorptive
bubble
separation
techniques**

CONTRIBUTORS

J. AROD
DIBAKAR BHATTACHARYYA
STANLEY E. CHARM
W. DAVIS, Jr.
ALBERT J. de VRIES
DAVID W. ECKHOFF
D. W. FUERSTENAU
ROBERT B. GRIEVES
P. A. HAAS
T. W. HEALY
C. JACOBELLI-TURI
DAVID JENKINS
BARRY L. KARGER
ROBERT LEMLICH
F. MARACCI
A. MARGANI
M. PALMERA
T. A. PINFOLD
V. V. PUSHKAREV
ALAN J. RUBIN
ELIEZER RUBIN
T. SASAKI
JAN SCHERFIG

adsorptive bubble separation techniques

Edited by **Robert Lemlich**

Department of Chemical
and Nuclear Engineering
University of Cincinnati
Cincinnati, Ohio

1972



Academic Press
New York and London

COPYRIGHT © 1972, BY ACADEMIC PRESS, INC.

ALL RIGHTS RESERVED

NO PART OF THIS BOOK MAY BE REPRODUCED IN ANY FORM,
BY PHOTOSTAT, MICROFILM, RETRIEVAL SYSTEM, OR ANY
OTHER MEANS, WITHOUT WRITTEN PERMISSION FROM
THE PUBLISHERS.

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1 7DD

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 75-154398

PRINTED IN THE UNITED STATES OF AMERICA

List of Contributors

Numbers in parentheses indicate the pages on which the authors' contributions begin.

- J. AROD (243), Service d'Analyse et de Chimie Appliquée, Centre d'Études Nucléaires de Cadarache, France
- DIBAKAR BHATTACHARYYA (183), Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky
- STANLEY E. CHARM (157), New England Enzyme Center, Tufts University Medical School, Boston, Massachusetts
- W. DAVIS, Jr. (279), Chemical Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee
- ALBERT J. de VRIES (7), Pechiney-Saint-Gobain, Centre de Recherches de la Croix-de-Berny, Antony, France
- DAVID W. ECKHOFF (219), H. F. Ludwig and Associates, New York, New York
- D. W. FUERSTENAU (91), Department of Materials Science and Engineering, University of California, Berkeley, California
- ROBERT B. GRIEVES (175, 183, 191), Department of Chemical Engineering, University of Kentucky, Lexington, Kentucky
- P. A. HAAS (279), Chemical Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee
- T. W. HEALY* (91), Department of Materials Science and Engineering, University of California, Berkeley, California
- C. JACOBELLI-TURI (265), Laboratorio di Metodologie Avanzate Inorganiche del Consiglio Nazionale delle Ricerche, Rome, Italy
- DAVID JENKINS (219), Department of Sanitary Engineering, University of California, Berkeley, California
- BARRY L. KARGER (145), Department of Chemistry, Northeastern University, Boston, Massachusetts
- ROBERT LEMLIICH (1, 33, 133), Department of Chemical and Nuclear Engineering, University of Cincinnati, Cincinnati, Ohio
- F. MARACCI (265), Laboratorio di Metodologie Avanzate Inorganiche del Consiglio Nazionale delle Ricerche, Rome, Italy
- A. MARGANI (265), Laboratorio di Metodologie Avanzate Inorganiche del Consiglio Nazionale delle Ricerche, Rome, Italy
- M. PALMERA (265), Laboratorio di Metodologie Avanzate Inorganiche del Consiglio Nazionale delle Ricerche, Rome, Italy
- T. A. PINFOLD (53, 75), Department of Chemistry including Biochemistry, University of the Witwatersrand, Johannesburg, South Africa
- V. V. PUSHKAREV (299), The Urals Kirov Polytechnical Institute, Sverdlovsk, U.S.S.R.

*Present address: Department of Physical Chemistry, University of Melbourne, Parkville, Victoria, Australia.

- ALAN J. RUBIN (199), Water Resources Center, College of Engineering, Ohio State University, Columbus, Ohio
- ELIEZER RUBIN (249), Department of Chemical Engineering, Technion - Israel Institute of Technology, Haifa, Israel
- T. SASAKI (273), Department of Chemistry, Faculty of Science, Tokyo Metropolitan University, Setagaya, Tokyo, Japan
- JAN SCHERFIG (219), Department of Sanitary Engineering, University of California, Irvine, California

Preface

This is the first comprehensive book to cover the various adsorptive bubble separation techniques. It is a contributed volume, with various authors for its twenty chapters.

The editor is responsible for defining the scope of the work, and in general for selecting the topic for each chapter. The authors of the chapters were also selected by the editor and invited to write on the basis of their specialized knowledge in their respective areas. However, each author was given wide latitude to treat his material as he saw fit. The overall result is a highly authoritative compilation which, it is hoped, will prove to be both informative and readable.

Chapter 1 introduces the various adsorptive bubble separation techniques. Chapter 2 deals with certain pertinent properties of foam which are common to many of them. Then, Chapters 3 through 8 individually discuss several of these techniques; namely, foam fractionation, ion flotation, precipitate flotation, mineral flotation, bubble fractionation, and solvent sublation. The remaining chapters, 9 through 20, summarize the results of numerous separations, as well as the results of additional investigations into the mechanisms of the various techniques. As a special feature of interest, the final six chapters (arranged in alphabetical order by country) comprise a summary of work, dealing principally with the separation of surfactants and metallic ions, at several places around the world.

The editor expresses his thanks to the contributors and to the staff of Academic Press for making this volume possible.

ROBERT LEMLICH

This page intentionally left blank

Contents

	List of Contributors	v
	Preface	vii
Chapter 1	Introduction	
	Robert Lemlich	
	I. Overview	1
	II. Classification of Techniques	2
	III. Droplet Analogs	3
	References	4
Chapter 2	Morphology, Coalescence, and Size Distribution of Foam Bubbles	
	Albert J. de Vries	
	I. Introduction	7
	II. Morphology and Structure of Foams	8
	III. Gas Diffusion in Foams	18
	IV. Thinning and Rupture of Bubble Walls	25
	References	30
Chapter 3	Principles of Foam Fractionation and Drainage	
	Robert Lemlich	
	I. Introduction	33
	II. Adsorption	34
	III. Column Operation	36
	IV. Foam	43
	V. Closure	48
	Symbols	49
	References	50
Chapter 4	Ion Flotation	
	T. A. Pinfold	
	I. Introduction	53
	II. Methodology	54
	III. Parameters Affecting the Process	56
	IV. Continuous Ion Flotation	64
	V. Analytical Applications	66
	VI. Theoretical Considerations	68
		ix

	VII. Uses	70
	VIII. Conclusion	72
	References	72
Chapter 5	Precipitate Flotation	
	T. A. Pinfold	
	I. Introduction	75
	II. Precipitate Flotation of the First Kind	77
	III. Precipitate Flotation of the Second Kind	86
	IV. Conclusion	88
	References	89
Chapter 6	Principles of Mineral Flotation	
	D. W. Fuerstenau and T. W. Healy	
	I. Introduction	92
	II. Measurement of Flotation Behavior	93
	III. Equilibrium Considerations in Flotation Systems	96
	IV. Adsorption of Organic and Inorganic Ions at Mineral-Water Surfaces	104
	V. Some Physical Chemical Variables in Flotation	111
	VI. Some Examples of Technological Flotation Separations	124
	VII. Flotation Kinetics	126
	VIII. Summary	129
	References	129
Chapter 7	Bubble Fractionation	
	Robert Lemlich	
	I. Introduction	133
	II. Theory	135
	III. Experimental Results	137
	Symbols	142
	References	143
Chapter 8	Solvent Sublation	
	Barry L. Karger	
	I. Introduction	145
	II. Experimental Design	147
	III. Characteristics of Solvent Sublation	149
	IV. Mechanism of Removal	153
	V. Relationship to Solvent Extraction	154

VI. Conclusion	155
References	156
Chapter 9	Foam Separation of Enzymes and Other Proteins
	Stanley E. Charm
I. Introduction	157
II. Fundamental Considerations	159
III. Foam Separation of Proteins	164
IV. Closure	173
References	174
Chapter 10	Foam Fractionation of Surfactants, Orthophosphate, and Phenol
	Robert B. Grieves
I. Batch and Continuous Separation of Cationic and Anionic Surfactants	175
II. Batch Separation of Orthophosphate and of Phenol	178
Symbols	180
References	181
Chapter 11	Ion, Colloid, and Precipitate Flotation of Inorganic Anions
	Robert B. Grieves and Dibakar Bhattacharyya
I. Batch Ion Flotation of Chromium(VI)	183
II. Continuous Ion Flotation of Chromium(VI)	184
III. Continuous Dissolved-Air Ion Flotation of Chromium(VI)	185
IV. Batch and Continuous Precipitate Flotation of Chromium(III)	186
V. Ion and Colloid Flotation of Cyanide Complexed by Iron	187
VI. Precipitate Flotation of Cyanide Complexed by Iron	188
References	189
Chapter 12	Flotation of Particulates: Ferric Oxide, Bacteria, Active Carbon, and Clays
	Robert B. Grieves
I. Colloidal Ferric Oxide	191
II. Six Species of Bacteria	193
III. Active Carbon with Adsorbed Phenol	194
IV. Clays and Clay Sediments: Clarification of Turbid Waters	195

	V. Effect of Particulates on Foam Separation of Surfactants	196
	References	197
Chapter 13	Removal and Use of Hydrolyzable Metals in Foam Separations	
	Alan J. Rubin	
	I. Introduction	199
	II. Experimental Methods and Materials	201
	III. Foam Separation of Hydrolyzable Metals	202
	IV. Microflotation for Removal of Colloids	214
	References	217
Chapter 14	Application of Adsorptive Bubble Separation Techniques to Wastewater Treatment	
	David Jenkins, Jan Scherfig, and David W. Eckhoff	
	I. Introduction	219
	II. Applications to Domestic Wastewater	223
	III. Applications to Industrial Wastes	238
	IV. Concluding Remarks	240
	References	241
Chapter 15	Separation of Surfactants and Metallic Ions by Foaming: Studies in France	
	J. Arod	
	I. Introduction	243
	II. Preliminary Study	243
	III. Adaptation of Foam Separation to Waste Treatment	245
	IV. Exploitation of a 100-liter/hr Pilot Plant	246
	V. Conclusion	247
	References	248
Chapter 16	Separation of Surfactants and Metallic Ions by Foaming: Studies in Israel	
	Eliezer Rubin	
	I. Introduction	249
	II. Adsorption to Gas-Liquid Interfaces	250
	III. Properties of Dynamic Foams	255

IV. Equipment Design and Performance	258
Symbols	263
References	264
Chapter 17	Separation of Metallic Ions by Foaming: Studies in Italy
	C. Jacobelli-Turi, F. Maracci, F. Margani, and M. Palmera
I. Ion Adsorption	265
II. Representative Separations	270
Symbols	272
References	272
Chapter 18	Separation of Particles, Molecules, and Ions by Foaming: Studies in Japan
	T. Sasaki
I. General Aspects of Separation by Bubbling	273
II. Ion Flotation	274
III. Molecule and Particle Flotations	275
References	277
Chapter 19	Separation of Surfactants and Metallic Ions by Foaming: Studies at Radiation Applications, Inc., and Oak Ridge National Laboratory, U.S.A.
	W. Davis Jr., and P. A. Haas
I. Origin and Objectives of Foam Fractionation Work at RAI and ORNL	279
II. Fractionation of Metal Ions from Nitrate Solutions	280
III. Screening of Surface-Active Agents	284
IV. Decontamination of Process Wastewater	285
V. Combined Foam Separation - Froth Flotation Process	288
VI. Some Comparisons between Static and Dynamics Surfaces	290
VII. Development of Countercurrent Foam Columns	291
VIII. Foam Drainage Model and Experimental Results	293
Symbols	295
References	296

**Chapter 20 Separation of Surfactants and Ions from Solutions
by Foaming: Studies in the U.S.S.R.**

V. V. Pushkarev

I. Introduction	299
II. Surfactant Separation	300
III. Ion Separation	307
References	313
Author Index	315
Subject Index	323

**adsorptive
bubble
separation
techniques**

This page intentionally left blank

Robert Lemlich

Department of Chemical and Nuclear Engineering
University of Cincinnati
Cincinnati, Ohio

I. Overview	1
II. Classification of Techniques	2
III. Droplet Analogs	3
References	4

I. OVERVIEW

All techniques or methods of separation, whether physical or chemical, are based on differences in properties. For example, among the more familiar techniques, distillation is based on differences in volatility, and liquid extraction is based on differences in solubility.

The *adsorptive bubble separation* techniques are among the less familiar methods. This generic name was first proposed by Lemlich (1966), with *adsubble* techniques as the convenient contraction. The full generic name has since been accepted by common consent (Karger *et al.*, 1967).

The adsubble techniques are based on differences in surface activity. Material, which may be molecular, colloidal, or macroparticulate in size, is selectively adsorbed or attached at the surfaces of bubbles rising through the liquid, and is thereby concentrated or separated. A substance which is not surface active itself can often be made effectively surface active through union with or adherence to a surface active *collector*. The substance so removed is termed the *colligend* (Sebba, 1962).

Adsubble processes can be found in nature: in sea foam and bubbling marshes. Among human endeavors, the earliest occurrence is probably among the culinary arts in such phenomena as the slightly bubble-aided floating of some constituents in certain boiling soups and other preparations. Another early example is in the pouring of beer. Certain components of the beer can concentrate in the foam to a sufficient degree to alter the flavor (Nissen and Estes, 1940).

In 1878 Gibbs derived the celebrated adsorption equation that bears his name (Gibbs, republished 1928). About the turn of the century, attempts were