DRYING'92 PART A

Drying'92 Part A

Proceedings of the 8th International Drying Symposium (IDS '92) Montreal, Quebec, Canada, August 2–5, 1992

edited by

A.S. Mujumdar

Department of Chemical Engineering, McGill University, Montreal, Quebec, Canada and Exergex Corporation, Brossard, Quebec, Canada



ELSEVIER SCIENCE PUBLISHERS B.V. Sara Burgerhartstraat 25 P.O. Box 211, 1000 AE Amsterdam The Netherlands

ISBN: 0-444-89393-8

© 1992 Elsevier Science Publishers B.V. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior written permission of the publisher, Elsevier Science Publishers B.V., Copyright & Permissions Department, P.O. Box 521, 1000 AM Amsterdam, The Netherlands.

Special regulations for readers in the U.S.A. - This publication has been registered with the Copyright Clearance Center Inc. (CCC), Salem, Massachusetts. Information can be obtained from the CCC about conditions under which photocopies of parts of this publication may be made in the U.S.A. All other copyright questions, including photocopying outside of the U.S.A., should be referred to the copyright owner, Elsevier Science Publishers B.V., unless otherwise specified.

No responsibility is assumed by the publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein.

pp. 74-91, 161-180, 190-199, 444-453, 585-594, 913-923, 941-952, 1227-1235, 1739-1744; copyright not transferred.

This book is printed on acid-free paper.

Printed in The Netherlands

Drying'92

Part A

PREFACE

DRYING'92 constitutes the formal proceedings of the 8th International Drying Symposium (IDS'92) held in Montreal, August 2-5, 1992. As the Founder and Program Chairman of this biennial symposium series, I am delighted that the response to the call for papers far exceeded my most optimistic expectations in view of the current economic slowdown all over the world. Indeed, over 300 papers were offered but unfortunately not all could be accommodated in the IDS'92 papers. Some of the papers presented at IDS'92 are included in the 10th Anniversary Special issue of Drying Technology - An International Journal, Volume 10, No. 4, 1992. These papers do not appear in these proceedings volumes.

The continuing growth in drying R&D around the world - and particularly the recognition by industry of the significance of the solids drying operation - is reflected in the ever-increasing number of papers offered and presented at IDS meetings, regardless of where they are held. The impetus for this growth is provided not only by the energy-intensiveness of thermal drying but also by the hitherto-neglected environmental implications (e.g. greenhouse gas emission due to burning of fossil fuels), product quality, productivity enhancement, safety of operation etc. Readers will find papers covering all of these aspects in *DRYING'92*.

A quick scanning of the Contents will reveal that all aspects of drying and selected topics in nonthermal dewatering are covered in both depth and breadth; almost all industrial sectors where drying is a significant operation are represented. In addition, there are papers from academia and industry, and from different disciplines and various parts of the world. Thus IDS'92 has succeeded in meeting the prime motivating criteria of the series viz. to provide a truly global forum for exchange of ideas across disciplines and to encourage cross-fertilization of ideas across industrial sector boundaries. Indeed, I believe that IDS actually stands for ideas, novel and creative ideas that should enhance drying technology in the long term.

Organization of a conference such as IDS'92 is necessarily a collective effort of numerous dedicated and enthusiastic individuals from all continents. I am grateful to my associates at McGill, members of our Advisory Panel, the professional societies and companies (who are listed on following pages) for their tangible support of IDS'92, various journal editors and members of my family as well as my extended family of Research Associates, Post-doctoral Fellows, visiting scientists and graduate students who were always there to assist me when needed.

A large number of individuals helped me with the massive editorial effort involved especially in view of the very stringent deadlines we, as well as the publisher, Elsevier, have had to adhere to. Dr. Bing Huang, Program Coordinator of IDS'92 and Dr. T. Kudra were immensely helpful in the editorial process. Purnima Mujumdar acted as the

editorial assistant for these volumes - just as effectively as she did for all the previous books on drying I have edited. Seyed Seyedien, Hamid Rabie, Dr. Stefan Grabowski and Dr. Cristina Ratti provided considerable assistance with the numerous chores involved in the organization of a conference such as *IDS* 92. Drs. Z. Koran, F. Ahrens, G.S.V. Raghavan and S. Sokhansanj acted as coordinators of various sessions. I am grateful to all these individuals for their invaluable assistance and counsel.

IDS'92 acknowledges with gratitude the effort of all the authors, members of the Advisory Panel, Keynote and Invited Lecturers, Session Co-chairmen and the Plenary Lecturer (Prof. M. Karel). The contributions made to the success of IDS'92 by Professor C.J. King, University of California at Berkeley as Chairman of the IDS Major Awards Committee, and by L.R. Genskow (Procter & Gamble co., Cincinnati, U.S.A.) are sincerely appreciated and acknowledged. The assistance of Exergex Corporation in providing most of the secretarial effort over a two year period is also acknowledged.

Finally, my sincerest thanks go to the staff of Elsevier Science Publishers, Amsterdam, The Netherlands, for their most efficient processing of *DRYING'92* in a remarkably short time from receipt of manuscripts in Amsterdam to delivery in Montreal. Consistent with the nature of IDS, this too has been a truly international effort. If any errors have crept into the editorial effort, I would like to apologize to the authors concerned.

Arun S. Mujumdar Editor Montreal, Canada

ACKNOWLEDGEMENTS

IDS 92 is grateful to the following professional organizations for their support as co-sponsors or co-operating societies:

Canadian Society for Chemical Engineering American Institute of Chemical Engineers American Society of Mechanical Engineers American Society of Agricultural Engineers Canadian Society of Agricultural Engineers Institute of Food Technologists International Microwave Power Institute Institution of Chemical Engineers (London, U.K.) Japan Society of Chemical Engineers Society of Powder Technology Japan Japan Society of Food Science and Technology Japan Society of Bioscience, Biotechnology and Agrochemistry Japan Society of Agricultural Machinery Chinese Chemical Engineering Institute Czech Academy of Sciences AFME (France) SCI (France) SFT (France) AFSIA (France) IUFOR

IDS'92 recognizes with gratitude the tangible support of the following companies which assisted with the preliminary organizational expenses for IDS'92 which stretched over nearly three years:

3M Company
TEC Corporation
Cargill Corporation
The Pillsbury Company
James River Corporation
Exergex Corporation
Rosin Americas Ltd.

The support of the following organizations in the form of Sponsored Major Awards at *IDS* 92 is gratefully acknowledged:

The Procter & Gamble Company (U.S.A)
ICI (U.K)
NGK Insulators (Japan)
AFME, SCI, SFT and AFSIA (France)
Marcel Dekker (U.S.A.)

All secretarial effort required for *IDS* 92 and related activities was provided over a two years period on complimentary basis by Exergex Corporation, Brossard, Quebec, Canada. The financial support of the Faculty of Graduate Studies and Research of McGill University is acknowledged.

We are grateful to the numerous international journals and newsletters which announced IDS'92 Call for Papers.

FUTURE MEETINGS:

IDS'94, Brisbane, Australia

IDS'96, Kiev, Ukraine

IDS'98, Thessaloniki, Greece

PROCEEDINGS OF IDS MEETINGS:

IDS'90, Prague, Czchoslovakia. Available as DRYING'91 from Elsevier, Amsterdam or affiliates in various countries.

Proceedings of IDS'88, IDS'86 and IDS'84 are available from Hemisphere Publishing Corp., a Div. of Taylor & Francis, N.Y., U.S.A.

IDS ADVISORY PANEL

M. Akritidis, Greece O. Alves-Filho, Brazil R.E. Bahu, U.K. I. Borde, Israel P. Dejmek, Sweden A. Dolinski, Ukraine W.J.M. Douglas, Canada I. Filkova, Czechoslovakia S.V. Fedosov, Russia L.R. Genskow, U.S.A. C.W. Hall, U.S.A. A. Hallstrom, Denmark M. Hasatani, Japan D. Heldman, U.S.A. L. Imre, Hungary G.D. Jinescu, Romania P.L. Jones, U.K. M. Karel, U.S.A. F. Kayihan, U.S.A. R.B. Keev, New Zealand J.J. Kelly, Ireland C.J. King, U.S.A. B. Kisakurek, Turkey

T. Kudra, Poland M. Lampinen, Finland J.R. Maa, Taiwan K.E. Millitzer, Germany A. Mulet Pons, Spain H. Muralidhara, U.S.A. M. Okazaki, Japan T. Ohlsson, Sweden Y.K. Pan, P.R. China O.E. Potter, Australia J.R. Puiggali, France V. Raghavan, Canada M. Roques, France E. Rotstein, U.S.A. G. Scalabrin, Italy E.U. Schlünder, Germany P.S. Schmidt, U.S.A. R.P. Singh, U.S.A. S. Sokhansanj, Canada M. Stefanovic, Yugoslavia C. Strumillo, Poland W. Tanthapanichakoon, Thailand E. Tsotsas, Germany S. Whitaker, U.S.A.

The Program Chairman of <u>IDS'92</u> is indebted to the members of the <u>IDS Advisory Panel</u> for their active contribution to the success of the IDS series. Without their enthusiastic participation, the series could not have flourished on the global scale it has.

CONTENTS

Preface	
Acknowledgements	/i
IDS Advisory Panel	i
PARI A	
SECTION I. PLENARY / KEYNOTES / INVITED LECTURES	
Optimization of Quality of Dehydrated Foods and Biomaterials	1.1
Measurement and Modelling of Intraparticle Drying Kinetics: A Review	
Food Drying and Quality Interactions	
Relating Moisture Transfer Rate in Rice to Kernel Quality	
Spray Drying - Maturity or Opportunities? 7 Richard E. Bahu, SPS, Harwell Laboratory, Oxfordshire, U.K.	
Drying of Ceramics Made by Sol-Gel Processing	
Electromagnetic Wave Energy in Drying Processes	4
Heat and Mass Transfer Considerations in Dielectrically-Enhanced Drying 13 P.S. Schmidt, T.L. Bergman and J.A. Pearce,	7
Center for Energy Studies, University of Texas, Austin, TX, USA Peishi Chen, Philip Morris Research and Development, Richmond, VA, USA	
Fundamentals of Enhanced Scalar Transport in Strongly Oscilating and/or Resonant Flow Fields as Created by Pulse Combustion	1
O. Keller, Sandia National Laboratories, Livermore, CA, USA	1
R.S. Gemmen, US DOE/Morgantown Energy Tech. Center, Morgantown, WV, USA R.W. Ozer, Bēpex Corporation, Minneapolis, MN, USA	

Effect of Operation Conditions of Drying and Pyrolysis on the formation of Fine Particles Produced by the Spray Pyrolysis Method	181
Deformation Characteristic of Ceramics During Drying	190
Advanced Dewatering Techniques and Their Impact on . Drying Technologies	200
Impinging Streams (IS) and Their Application to Drying	209
Novel Drying Technologies for Particulates, Slurries and Pastes	224
Have a Marie State and Statement of Manufacture 1953	
SECTION II. FUNDAMENTAL STUDIES IN DRYING	241
Estimation of Drying Rate and Determination of Moisture Diffusivity for Non-Hygroscopic Porous Material Based on the	
Characteristic Function for the Regular Regime	
Capillary Condensation, Hysteresis and Image Analysis	
Prom Pore-Size Distribution to Moisture Transport Properties: Particular Problems for Large Pore-Size Distributions (Invited)	263
The Evaporation of Ternary Liquid Azeotropes to Air	283
Drying Shrinkage and Stresses A.A.J. Ketelaars, W.J. Coumans Eindhoven Univ. of Technology, Eindhoven, The Netherlands W. Jomaa, J.R. Puiggali, L.E.P.TENSAM, Talence, France	293
Behaviour of Multilayers Walls with Different Vapor Permeability of External Coating	304

Measurement of Water Activity at High Temperature	. 312
Simultaneous Mass and Heat Transfer During Drying of Unsaturated Capillary Porous Solids Containing Multicomponent Liquid Mixtures	. 322
J. Martínez, Royal Inst. of Technology, Stockholm, Sweden	
Sorption Isotherms for Multicomponent Solid Mixture	. 334
Determination of Diffusion Coefficients from	
Experimental Moisture Concentration Profiles in Clay	
A.A.J. Ketelaars, O. Lauf, W.J. Coumans, P.J.A.M. Kerkhof	
Eindhoven University of Technology, Eindhoven, The Netherlands	
The Wet Surface Reduction During the First Drying Period	
A. Belhamri, JP. Fohr, UA CNRS, Poitiers, France	
Drying of Polymers, Modeling with Diffusion-Evaporation and Shrinkage	364
D. Berthet, A. Bakhouya, J. Bouzon and J.M. Vergnaud	
University of St. Etienne, Saint Etienne, France	
Low-Temperature Vacuum Desorption of a	
Multicomponent Moisture in Freeze Drying	. 374
J.F. Nastaj, Technical University of Szczecin, Szczecin, Poland	
The Characteristics of Thermal Control of	
Freeze-Drying Processes in Porous Plates, Cylinders and Spheres	. 384
Sui Lin, Concordia University, Montreal, Canada	
SECTION III.	103
MODELLING AND SIMULATION	. 395
Microscopic Models for the Study of Drying of Capillary Porous Media	. 397
O.A. Plumb, Washington State Univ., Pullman, WA, USA	
M. Prat, Institut de Mecanique des Fluides de Toulouse, Toulouse, France	
Development and Validation of a Computational Model for	
Spray-Gas Mixing in Spray Dryers	407
D.M. Livesley, R.F. Gillespie, M.L. Yeoman	
AEA Industrial Technology, Culham Laboratory, Oxfordshire, U.K.	
D.E. Oakley, Harwell Laboratory, Oxfordshire, U.K.	
B. Elhaus, University of Bremen, Bremen, Germany	
C.K. Ranpuria, T. Taylor, Unilever Research, Wirral, U.K. W. Wood, ICI Fine Chemicals, Manchester, U.K.	
. Troot, 161 The Chemicus, Munchester, U.K.	
Modelling the Temperature Profiles within Boards During	
the High-Temperature Drying of Pinus Radiata Timber	417

T.A.G. Langrish, University of Sydney, N.S.W., Australia	
Model of Flash Drying Jaakko Saastamoinen, Technical Research Centre of Finland, Jyvaskyla, Finland	434
Modelling Agglomeration Effects in Pneumatic Conveying Dryers I.C. Kemp and R. E. Bahu, SPS, Harwell Laboratory, Oxfordshire, U.K.	444
Mathematical Modelling of the Inductively Heated Rotary Dryer 1. Zbicinski, Technical Univ. of Lodz, Lodz, Poland J.T. Griffith, EA Technology, Capenhurst, Chester, U.K.	454
Mathematical Modelling of Fluidized Bed Drying with Superheated Vapor	464
Mathematical Modelling of Solar Dryers with Chimney	473
Drying of Nylon Pellet	482
Modelling of Two-component Fluid Bed Driers: An Approach to the Evaluation of the Drying Time	493
SECTION IV. SPRAY DRYING	503
Concentrated Kraft Black Liquor Atomization Using a Two-Fluid Atomizing Nozzle P.R. Stuart and W.H. Gauvin, McGill University, Montreal, Canada	505
Application of Multiobjective Optimization to Spray Drying	515
Application of Laser Measurement Methods on Sprays of Non-Transparent Fluids . B. Elhaus, G. Schulte, University Bremen, Bremen, F.R. Germany D.M. Livesley, Harwell Laboratory, U.K.	524
Spray Drying as a Shaping Technique for Catalyst Production	533

Liquid Phase Distribution in a Spray Formed by Pneumatic Nozzles in	
the Spray Dryer Chamber	543
Academy of Science of the Republic Belarus, Minsk, Belarus	
SECTION V.	
DIELECTRIC DRYING	551
Convective and Microwave Enhanced Drying of Glass Beads I.W. Turner, Queensland Univ. of Technology, Brisbane, Australia V. Rudolph, University of Queensland, Brisbane, Australia	
A Step Wise Modelisation for Combined Microwave Convective Drying	
of Deformable Materials M.A. Roques, F. Zagrouba, E.N.S.I.C., L.P.C.I., France P. Perre, E.N.G.R.E.FL.E.M.T.A, Nancy, France N. Kechaon, E.N.I.G., Gabes, Tunisie	573
A Comparison of Conventional and Microwave Augmented Freeze Drying of Peas J. S. Cohen, J. A. Ayoub and T.C.S. Yang US Army Natick Research, Natick, MA, USA	585
Microwave Drying of Agar Gels: Kinetic Parameters	595
Microwave Drying of Corn	607
Microwave Drying of Light Concrete: From Transport Mechanisms to Explanation of Energy Savings T. Constant, C. Moyne, LEMTA, Vandoeuvre, France P. Perre, ENGREF, Nancy, France	
The Four Phases of Micro-Wave and Convective Combined Drying	627
The Effect of Combined Microwave and Convective Drying of Porous Media on Drying Kinetics	635
Drying of Heat Sensitive Materials on Inert Particles with Combined (Convective and Microwave) Heat Transfer T. Szentmarjay, A. Szalay, Hungarian Academy of Sciences, Veszprém, Hungary F. Zagrouba, ENSIC,-INPL, Nancy, France M.A. Rouques, ESIGTI, Univ. de Pau, Pau, France	650

Rodriguez G., Vasseur, J., Trystram, G., ENSIA, Massy, France	050
SECTION VI INFRARED DRYING	667
Graphite Slurry Dehydration by Infrared Radiation under Vacuum Conditions	669
P. Dontigny, P. Angers, M. Supino, L.T.E.E. d' Hydro-Quebec, Shawinigan, Que., Canada	
Optimization of a Drying Process using Infrared Radio Frequency	
and Convection Heating	679
Studies on Infrared and Convective Drying of Non Hygroscopic Solids	685
Convective Transport in Infrared Drying	695
A.S. Mujumdar, McGill University, Montreal, Canada	
Application of Infra-Red Radiation for Drying of Particulate Materials	704
Optical Characteristics of Gelatinous Materials	
in Infrared Radiation Drying	712
Tokyo University of Agriculture and Technology, Tokyo, Japan	
Preliminary Study of Drying of Coated Film Heated by Infrared Radiation	722
SECTION VII. DRYING OF PARTICULATE MATERIALS	729
Drying Performances and Heat Transfer in a Vibrated Fluidized Bed	/31
Drying of Granular Materials by Temperature Program	741

is.

Xiaomei Song, The Norwegian Institute of Technology, Trondheim, Norway	
Drying and Particle Agglomeration Technology	. 750
Performance of an Experimental Vibro-Spouted Bed Dryer	
SECTION VIII. DRYING OF FOODS	. 773
Mass Transfer and Volatiles Retention During Foam-Mat Drying of Food Models	. 775
Model Selection in Air Drying of Foods	. 785
Spray Drying Leaflash Technique: Application to Liquid Food Products	. 795
J.C. Laguerre, ISAB, Cergy Pontoise, France O. Techasena, CEMAGREF, Antony, France A. Lebert, INRA, Massy, France J.J. Bimbenet, ENSIA, Massy, France	. 805
Drying of Desiccated Coconut on Vibrating Fluidised Bed Dryer	815
Cane Sugar Drying in Fluidized Bed	
Analysis of Dryers Performance for Tropical Foodstuffs Using the Characteristic Drying Curve Concept	834
Influence of Fat Content on the Drying of Meat Products	844
Conservation of High-Moisture Dried Apricots	854

A. Mulet, Univ. Politécnica València, Spain A. Berna, Univ. València, Spain	
A Generalized Drying Curve for Shrinking Food Materials	. 86-
Drying Parameters to Obtain "Banana-Passa"	. 874
Heat and Mass Transfer in Externally Controlled Drying of Vegetables P.P. Lewicki, D. Witrowa, Warsaw Agricultural Univ., Warsaw, Poland	. 884
Secondary Surface and its Detection on a Drying Process of Persimmons Setsuo Hayashi, Toyama Prefectural University, Toyama, Japan	892
Rates of Loss of Volatile Compounds During Drying of Suspended Drops J.M. Sunkel and C.J. King, Univ. of California, Berkeley, CA, USA	901
PART B	
SECTION IX. DRYING OF PAPER	911
A Simulation Model for Paper Machine Dryer Section	913
Optimizing Efficiency of Short Wave Infrared Dryer	924
The Potential for Higher Drying Rates in Cylinder Drying of Paper J.D. Lindsay, Inst. of Paper Science and Tech., Atlanta, GA, USA A. Flaberl and D. Poirier, ABB Flakt Ross Inc., LaSalle, Quebec, Canada	931
Theoretical and Experimental Investigation of Paper Drying Using Gas-Fired IR Dryer HD. Kuang, J. Thibault, B.P.A. Grandjean Université Laval, Saint-Foy, Québec, Canada R. Chen, CRPP, Université du Québec à Trois-Rivières, Trois-Rivières, Québec, Canada	941
A Drying Comparison of Radial Jet Reattachment and Standard In-Line Jet Impingement	953