


Dave J. Adams • Paul J. Dyson • Stewart J. Tavener

Chemistry in Alternative Reaction Media

 WILEY

Chemistry In Alternative Reaction Media

Dave J. Adams

University of Leicester, UK

Paul J. Dyson

École Polytechnique Fédérale de Lausanne, Switzerland

and

Stewart J. Tavener

University of York, UK



Chemistry In
Alternative
Reaction Media

Chemistry In Alternative Reaction Media

Dave J. Adams

University of Leicester, UK

Paul J. Dyson

École Polytechnique Fédérale de Lausanne, Switzerland

and

Stewart J. Tavener

University of York, UK



Copyright © 2004

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester,
West Sussex PO19 8SQ, England

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk

Visit our Home Page on www.wileyeurope.com or www.wiley.com

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, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 33 Park Road, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Library of Congress Cataloging-in-Publication Data

Chemistry in alternative reaction media / Dave Adams, Paul Dyson, and Stewart Tavener.
p. cm.

Includes bibliographical references and index.

ISBN (invalid) 0-471-49849-1 (alk. paper) – ISBN 0-471-49849-1 (paper : alk. paper)

1. Solvents. 2. Solvation. 3. Chemical reactions. 4. Chemical kinetics. I. Adams, Dave (Dave J.) II. Dyson, Paul J. III. Tavener, Stewart.

QD544.C44 2004

541.3'9 – dc21

2003047967

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 0-471-49848-3 (Cloth)

ISBN 0-471-49849-1 (Paper)

Typeset in 10/12pt Times by Laserwords Private Limited, Chennai, India

Printed and bound in Great Britain by Biddles Ltd, Guildford, Surrey

This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

CONTENTS

Preface	xi
Abbreviations and Acronyms	xv
1 Chemistry in Alternative Reaction Media	1
1.1 Economic and Political Considerations	2
1.2 Why Do Things Dissolve?	6
1.3 Solvent Properties and Solvent Classification	8
1.3.1 Density	8
1.3.2 Mass Transport	9
1.3.3 Boiling Point, Melting Point and Volatility	10
1.3.4 Solvents as Heat-Transfer Media	11
1.3.5 Cohesive Pressure, Internal Pressure, and Solubility Parameter	11
1.4 Solvent Polarity	13
1.4.1 Dipole Moment and Dispersive Forces	14
1.4.2 Dielectric Constant	14
1.4.3 Electron Pair Donor and Acceptor Numbers	16
1.4.4 Empirical Polarity Scales	17
1.4.5 E_T^N and $E_T(30)$ Parameters	18
1.4.6 Kamlet–Taft Parameters	21
1.4.7 Hydrogen Bond Donor (HBD) and Hydrogen Bond Acceptor (HBA) Solvents	23
1.5 The Effect of Solvent Polarity on Chemical Systems	24
1.5.1 The Effect of Solvent Polarity on Chemical Reactions	24
1.5.2 The Effect of Solvent Polarity on Equilibria	26
1.6 What is Required from Alternative Solvent Strategies?	28
References	30
2 Multiphasic Solvent Systems	33
2.1 An Introduction to Multiphasic Chemistry	33
2.1.1 The Traditional Biphasic Approach	34
2.1.2 Temperature Dependent Solvent Systems	34
2.1.3 Single- to Two-Phase Systems	35
2.1.4 Multiphasic Systems	35
2.2 Solvent Combinations	36
2.2.1 Water	37
2.2.2 Fluorous Solvents	38

2.2.3	Ionic Liquids	38
2.2.4	Supercritical Fluids and Other Solvent Combinations	38
2.3	Benefits and Problems Associated with Multiphasic Systems	39
2.3.1	Partially Miscible Liquids	40
2.4	Kinetics of Homogeneous Reactions	43
2.4.1	Rate is Independent of Stoichiometry	44
2.4.2	Rate is Determined by the Probability of Reactants Meeting	45
2.4.3	Rate is Measured by the Concentration of the Reagents	45
2.4.4	Catalysed Systems	47
2.5	Kinetics of Biphasic Reactions	47
2.5.1	The Concentration of Reactants in Each Phase is Affected by Diffusion	47
2.5.2	The Concentration of the Reactants and Products in the Reacting Phase is Determined by Their Partition Coefficients	49
2.5.3	The Partition Coefficients of the Reactants and Products May Alter the Position of the Equilibrium	50
2.5.4	Effect of Diffusion on Rate	53
2.5.5	Determining the Rate of a Reaction in a Biphasic System	54
2.6	Conclusions	55
	References	55
3	Reactions in Fluorous Media	57
3.1	Introduction	57
3.2	Properties of Perfluorinated Solvents	58
3.3	Designing Molecules for Fluorous Compatibility	60
3.4	Probing the Effect of Perfluoroalkylation on Ligand Properties	64
3.5	Partition Coefficients	66
3.6	Liquid–Liquid Extractions	67
3.7	Solid Separations	68
3.8	Conclusions	71
	References	71
4	Ionic Liquids	75
4.1	Introduction	75
4.1.1	The Cations and Anions	77
4.1.2	Synthesis of Ionic Liquids	77
4.2	Physical Properties of Ionic Liquids	80

4.3	Benefits and Problems Associated with Using Ionic Liquids in Synthesis	88
4.4	Catalyst Design	90
4.5	Conclusions	92
	References	92
5	Reactions in Water	95
5.1	The Structure and Properties of Water	95
5.1.1	The Structure of Water	95
5.1.2	Near-Critical Water	99
5.1.3	The Hydrophobic Effect	99
5.1.4	The Salt Effect	100
5.2	The Benefits and Problems Associated with Using Water in Chemical Synthesis	101
5.3	Organometallic Reactions in Water	103
5.4	Aqueous Biphasic Catalysis	104
5.4.1	Ligands for Aqueous–Organic Biphasic Catalysis	104
5.5	Phase Transfer Catalysis	109
5.5.1	The Transfer of Nucleophiles into Organic Solvents	112
5.5.2	Mechanisms of Nucleophilic Substitutions Under Phase Transfer Conditions	112
5.5.3	The Rates of Phase Transfer Reactions	114
5.5.4	Using Inorganic Reagents in Organic Reactions	119
5.6	Organometallic Catalysis under Phase Transfer Conditions	122
5.7	Triphase Catalysis	123
5.7.1	Mixing Efficiency in Solid–Liquid Reactions	126
5.8	Conclusions	126
	References	126
6	Supercritical Fluids	131
6.1	Introduction	131
6.2	Physical Properties	132
6.3	Local Density Augmentation	135
6.4	Supercritical Fluids as Replacement Solvents	136
6.5	Reactor Design	138
6.6	Spectroscopic Analysis of Supercritical Media	141
6.6.1	Vibrational Spectroscopy	141
6.6.2	NMR Spectroscopy	142
6.7	Reactions in Supercritical Media	143
6.8	Conclusions	145
	References	146
7	Diels–Alder Reactions in Alternative Media	149
7.1	Diels–Alder Reactions in Water	150

7.2	Diels–Alder Reactions in Perfluorinated Solvents	153
7.3	Diels–Alder Reactions in Ionic Liquids	153
7.4	Diels–Alder Reactions in Supercritical Carbon Dioxide	155
7.5	Conclusions	156
	References	156
8	Hydrogenation and Hydroformylation Reactions in Alternative Solvents	159
8.1	Introduction	159
8.2	Hydrogenation of Simple Alkenes and Arenes	161
8.2.1	Hydrogenation in Water	163
8.2.2	Hydrogenation in Ionic Liquids	166
8.2.3	Hydrogenation in Fluorous Solvents	169
8.2.4	Hydrogenation in Supercritical Fluids	170
8.3	Hydroformylation Reactions in Alternative Media	171
8.3.1	Hydroformylation in Water	171
8.3.2	Hydroformylation in Ionic Liquids	172
8.3.3	Hydroformylation in Fluorous Solvents	174
8.3.4	Hydroformylation in Supercritical Fluids	178
8.4	Conclusions	179
	References	179
9	From Alkanes to CO₂: Oxidation in Alternative Reaction Media	181
9.1	Oxidation of Alkanes	183
9.2	Oxidation of Alkenes	184
9.3	Oxidation of Alcohols	188
9.4	Oxidation of Aldehydes and Ketones	190
9.5	Destructive Oxidation	191
9.6	Conclusions	192
	References	193
10	Carbon–Carbon Bond Formation, Metathesis and Polymerization	195
10.1	Carbon–Carbon Coupling Reactions	195
10.1.1	Heck Coupling Reactions	196
10.1.2	Suzuki Coupling Reactions	199
10.1.3	Reactions Involving the Formation of C=C Double Bonds	201
10.2	Metathesis Reactions	202
10.2.1	Ring Opening Metathesis Polymerization	202
10.2.2	Ring Closing Metathesis	204
10.3	Polymerization Reactions in Alternative Reaction Media	205
10.3.1	Polymerization Reactions in Water	206

10.3.2	Polymerization Reactions in Supercritical Carbon Dioxide	208
10.3.3	Polymerization in Fluorous Solvents	214
10.4	Conclusions	215
	References	215
11	Alternative Reaction Media in Industrial Processes	217
11.1	Obstacles and Opportunities for Alternative Media	217
11.2	Reactor Considerations for Alternative Media	219
11.2.1	Batch Reactors	219
11.2.2	Flow Reactors	220
11.2.3	New Technology Suitable for Multiphasic Reactions	222
11.3	Industrial Applications of Alternative Solvent Systems	223
11.3.1	The Development of the First Aqueous–Organic Biphase Hydroformylation Plant	224
11.3.2	Other Examples of Processes Using Water as a Solvent	227
11.3.3	Scale-Up of PTC Systems	227
11.3.4	Thomas Swan Supercritical Fluid Plant	229
11.3.5	Other Applications of Supercritical Carbon Dioxide	230
11.4	Outlook for Fluorous Solvents and Ionic Liquids	232
11.5	Conclusions	233
	References	234
Index		237

Preface

Sipping a cup of decaffeinated coffee the reader may wonder on the somewhat unusual classification of solvents as ‘alternative’: alternatives to what? And why would we need alternative media for doing chemistry or for any other purpose? These may be the first questions of those who are just starting to discover the exciting new developments on using solvents other than volatile and often toxic organics for synthesis and especially for catalytic synthetic reactions. Yes, indeed, the vast majority of synthetically useful reactions do not take place between isolated entities in the gas phase; the science of chemistry has been developed and still mostly practiced in solutions where the reactants of the chemical transformation are molecularly dispersed by virtue of their interaction with the molecules making the majority of the liquid phase, i.e. the solvent. The thermodynamics of solutions is one of the oldest and most meticulously developed field of physical chemistry and serves as a fundament for chemical engineering. Solvents for a reaction are chosen according to their ability to dissolve the important ingredients of the reaction: solubility of the reactants, products and often the intermediates should carefully be considered. Traditionally, and logically from solubility aspects, the most important syntheses are run in organic solvents, but it is here, where several problems accumulated over the years. First and foremost, more and more organic solvents are blacklisted due to their damaging effect on human health or on the environment in general. Second, the synthesis of fine chemicals requires catalysts of highly sophisticated architecture and this is synonymous to those being extremely expensive. Such precious catalysts simply cannot be allowed to decompose during the workup phase of synthesis, often involving distillation.

From these considerations several new approaches emerged to reduce the risks and disadvantages of using traditional organic solvents by replacing them with so called *alternative* ones, the list of which include water, fluoruous solvents, supercritical fluids and ionic liquids. Note, that *alternative* does not necessarily mean *new* or newly discovered; in fact, most of these solvents have been around for several decades (not even mentioning water). What is really new is their use as alternatives to common organic solvents. All these liquids can be applied as the sole solvent in a given reaction, but most often biphasic or multiphasic reaction media are designed on the basis of the limited solubility of these liquids in each other. One should even add, that a proper combination of traditional organic solvents may result in a biphasic. By now probably all the possible permutations of the mentioned five general solvent classes have been demonstrated applicable for multiphase synthesis, the best known examples being the

Shell higher olefin process (organic/organic) and the Ruhrchemie-Rhône Poulenc propene hydroformylation process (aqueous/organic). The diversity of the applications may confuse the newcomer but it is not easy to comprehend even by the more experienced. A guide to this field may help a lot, and this is why the book of Adams, Dyson and Tavener is most welcome.

Of course, there are numerous reviews and several edited books on certain aspects of the use of a given solvent class in organic (and more rarely, inorganic) synthesis. But this book represents the first approach to describe the properties, physical chemical characterization and synthetic use of water, fluoruous solvents, supercritical fluids and ionic liquids from a unified view. Numerous tables and graphs help the reader not only to learn about the properties of these alternative solvents (not widely available elsewhere, and certainly not in the same publication) but also to discover the relation between the chemical structure and solvent ability. Perhaps the most attractive feature of the book is the well balanced combination of elementary physical chemistry (dissolution, solvent properties and characterization, polarity scales, solvent effects on kinetics, and the like) with the most advanced use of these principles to characterize such hard-to-handle solvents as supercritical fluids and ultrapure ionic liquids. In this way the authors succeed in bridging the gap between the often unusual features of the so-called alternative reaction media and their sound interpretation by chemical thermodynamics and kinetics. To see a substance, composed entirely of ions, flowing like water at room temperature may be a shocking experience, but this is not more shocking than to feel the sharp *fall* of temperature in a vigorous endothermic reaction made possible by a large increase in entropy (such as, for instance, the one between thionyl chloride and hydrated cobalt(II) chloride). Although in our everyday life we are not *used to* such phenomena they still surround us and it is just more than appropriate to make use of the unusual properties of *alternative solvents* in catalysis and synthesis, beyond the extraction of caffeine from the beans with supercritical carbon dioxide.

This book of Adams, Dyson and Tavener does not intend to give a last minute overview of all the applications using alternative solvents for chemical purposes; taking the fast pace with which research in this area moves this would be a vain attempt anyway. What they do, instead, is the presentation of the main concepts and the description of the most important and perhaps most representative examples of biphasic catalytic processes; these are supplemented by carefully chosen literature references. Moreover, experimental techniques to study such reactions are also described that will prove most useful in such unusual cases as, the investigations applying supercritical fluids. The outspoken intention of the authors is to give a guide, based on solid thermodynamic and kinetic basis, for those who wish to be familiar with the properties and with the fascinating possibilities alternative solvents offer to devise more efficient and less hazardous (green) chemical processes. I am convinced, that the prospective readers, from university students to industrial experts, will all find this book timely, clearly written and useful in their work.

After all: we all need more efficient and less hazardous chemical processes.
And for that reason we all need the use of alternative solvents.

July 11, 2003.

Ferenc Joó
University of Debrecen

Abbreviations and Acronyms

α	Kamlet–Taft hydrogen bond donor parameter
AIBN	2,2'-azobis(isobutyronitrile)
AN	electron pair acceptor number
β	Kamlet–Taft hydrogen bond acceptor parameter
Bp	boiling point
bipy	2,2'-bipyridine
c	cohesive pressure (cohesive energy density)
CED	cohesive energy density (cohesive pressure)
CFC	chlorofluorocarbon
cod	cyclooctadiene
δ	chemical shift (in NMR)
δ	Hildebrandt's solubility parameter
dba	dibenzylideneacetone
DMF	<i>N,N</i> -dimethylformamide
DMSO	dimethyl sulfoxide
DN	electron pair donor number
DN ^N	normalized electron pair donor number
dppe	bis(diphenylphosphino)ethane
dppf	1,1'-bis(diphenylphosphino)ferrocene
ϵ_0	permittivity of a vacuum
ϵ_r	dielectric constant or relative permittivity
ee	enantiomeric excess
$E_T(30)$	energy of transition for Reichardt's betaine dye
E_T^N	normalized energy of transition for Reichardt's betaine dye
FC-72	<i>n</i> -perfluorohexane
FRPSG	fluorous reverse phase silica gel
HBA	hydrogen bond acceptor
HBD	hydrogen bond donor
HOMO	highest occupied molecular orbital
HPLC	high pressure liquid chromatography
$k, k_1, k_2, k_{\text{obs}}$	rate constants
IL	ionic liquid
IR	infrared
K	equilibrium constant
l	length
LDPE	low density polyethylene

LUMO	lowest unoccupied molecular orbital
μ	dipole moment
m	mass
Mp	melting point
MS	mass spectrometry
NAILs	nonaqueous ionic liquids
nbd	norbornadiene
NCW	near-critical water
NMR	nuclear magnetic resonance
π^*	Kamlet–Taft general polarity parameter
π	internal pressure
P	partition coefficient
P	pressure
P_c	critical pressure
PP2	perfluoromethylcyclohexane
PP3	perfluorodimethylcyclohexane
PTC	phase transfer catalysis/catalyst
Q, Q ⁺	quaternary ammonium or phosphonium (or other cation in phase transfer reactions)
ρ_c	density at critical point
R _f	perfluoroalkyl group
RMM	relative molecular mass
sc	supercritical
SCF	supercritical fluid
T_c	critical temperature
TEMPO	2,2,6,6-tetramethylpiperidiny-1-oxyl
THF	tetrahydrofuran
TMS	tetramethylsilane
tppms	monosulfonated triphenylphosphine
tppts	trisulfonated triphenylphosphine
UV-vis	ultraviolet – visible spectroscopy
VOCs	volatile organic compounds
z	charge

IONIC LIQUID CATIONS

[mmim]	1,3-dimethylimidazolium
[emim]	1-ethyl-3-methylimidazolium
[bmim]	1-butyl-3-methylimidazolium
[hmim]	1-hexyl-3-methylimidazolium
[omim]	1-octyl-3-methylimidazolium
[dmim]	1-decyl-3-methylimidazolium
[bdmim]	1-butyl-2,3-dimethylimidazolium