

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/260245746>

Handbook on Ice Slurries – Chapter 3: Fluid Dynamics

Chapter · January 2005

CITATIONS

0

READS

248

7 authors, including:



Christian Doetsch

Fraunhofer Institute for Environmental, Safet...

100 PUBLICATIONS 494 CITATIONS

[SEE PROFILE](#)



Andrej Kitanovski

University of Ljubljana

85 PUBLICATIONS 1,313 CITATIONS

[SEE PROFILE](#)



Didier Vuarnoz

École Polytechnique Fédérale de Lausanne

83 PUBLICATIONS 322 CITATIONS

[SEE PROFILE](#)



Issa Chaer

London South Bank University

55 PUBLICATIONS 364 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Understanding and Modelling Thermal Energy Demand and Emissions in Urban Environments [View project](#)



IIR Mitigation of Direct Emissions of Greenhouse Gases in Refrigeration [View project](#)

All content following this page was uploaded by [Beat Frei](#) on 11 January 2016.

The user has requested enhancement of the downloaded file.

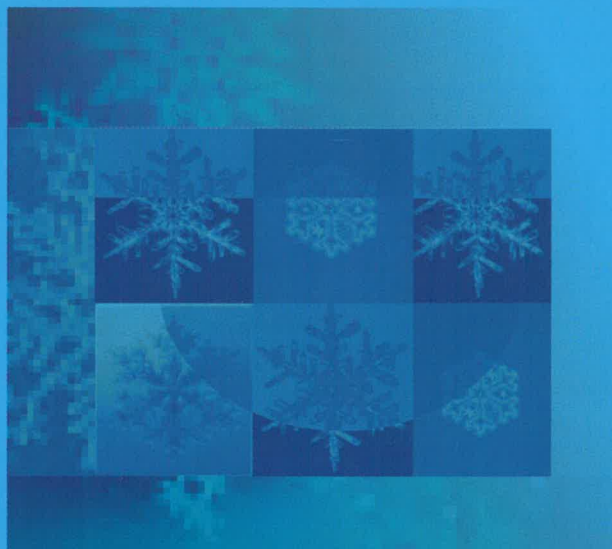


Handbook on Ice Slurries

- Fundamentals and Engineering -

Editors:

Michael Kauffeld, Masahiro Kawaji, Peter W. Egolf



**Extensively reviewed by
Åke Melinder, Tom W. Davies**

Published by:

**International Institute of Refrigeration
(IIR)**





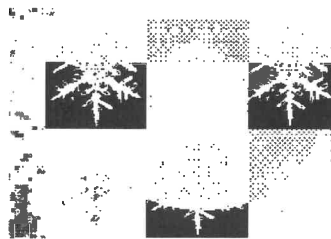
Handbook on Ice Slurries

– Fundamentals and Engineering –

Editors:

Michael Kauffeld, Masahiro Kawaji, Peter W. Egolf

**Extensively reviewed by
Åke Melinder, Tom W. Davies**



Published by

INTERNATIONAL INSTITUTE OF REFRIGERATION

177 boulevard Malesherbes – 75017 Paris, France

Tel.: +33 1 4227 3235 – Fax: +33 1 4763 1798

E-mail: iifiir@iifiir.org – Web site : www.iifiir.org

ISBN n° 2-913149-42-1

Copyright and Disclaimer

“The information provided in this document is based on the current state of art and is designed to assist engineers, scientists, companies and other organizations. It is a preliminary source of information that will need to be complemented prior to any detailed application or project. Whilst all possible care has been taken in the production of this document, the IIR, its employees, officers and experts cannot accept any liability for the accuracy or correctness of the information provided nor for the consequences of its use or misuse.

For full or partial reproduction of anything published in this document, proper acknowledgement should be made to the original source and its author(s). No parts of the book may be commercially reproduced, recorded and stored in a retrieval system or transmitted in any form or by any means (mechanical, electrostatic, magnetic, optic photographic, multimedia, Internet-based or otherwise) without permission in writing from the IIR.

© Copyright 2005 International Institute of Refrigeration

— Table of contents —

Foreword	9
Preface	10
1. Summary of Ice Slurry Technology	11
1.1 Introduction	11
1.2 Existing technologies	11
1.2.1 Heterogeneous nucleation	12
1.2.2 Homogeneous or spontaneous nucleation	12
1.3 Modern ice slurry applications	12
1.4 International Institute of Refrigeration (IIR) Working Party on Ice Slurries	13
1.4.1 Scientific challenges.....	13
1.4.2 Technical challenges	14
1.4.3 Objectives of the working party	14
1.5 Research institutes.....	15
1.6 Conclusions and outlook on the use of ice slurry	15
1.7 Other Phase Change Slurries (PCSs).....	15
1.7.1 Dry ice/carbon dioxide slurry.....	16
1.7.2 Clathrate slurry	16
1.7.3 Micro-emulsion slurry.....	17
1.7.4 Shape-stabilized PCM slurry.....	17
1.7.5 Microencapsulated PCM slurry.....	17
1.7.6 Polyethylene pellets.....	18
Literature cited in Chapter 1.....	18
2. Ice Creation, Thermophysical Properties of Ice Slurries and Other Characteristics.....	19
2.1 The formation of ice	19
2.1.1 Introduction	19
2.1.2 Metastable state – supercooled water.....	19
2.1.3 Nucleation	19
2.1.4 Effect of additives	24
2.2 Crystal growth	24
2.2.1 Initial crystal growth	24
2.2.2 Further processes affecting the crystal size.....	26
2.3 Types of ice crystals and ice particles	29
2.3.1 Shape parameters.....	30
2.3.2. Ice particle model	32
2.3.3 Measurements and statistics	33
2.4 Properties of aqueous solutions and ice	33
2.4.1 Introduction	33
2.4.2 Thermophysical properties of aqueous solutions	34
2.4.3 Freezing-point temperature of aqueous solutions	36
2.4.4 Thermophysical properties of ice	36
2.5 Physical properties of ice slurry	37
2.5.1 Freezing point temperature and ice concentration	37

2.5.2	Viscosity	39
2.5.3	Thermal conductivity	40
2.5.4	Enthalpy and enthalpy phase diagrams of aqueous solutions	41
2.6	<i>Safety, ecology and corrosion aspects of aqueous solutions</i>	48
2.6.1	General characteristics of additives used as aqueous solutions	48
2.6.2	General explanation of symbols	48
2.6.3	Comments on each type of aqueous solution	49
2.6.4	Corrosion behaviour and material compatibility	50
	<i>Literature cited in Chapter 2</i>	50
3.	Fluid Dynamics	55
3.1	<i>Rheology</i>	55
3.1.1	State of the art of ice slurry rheology	59
3.2	<i>Flows in tubes and pattern formation</i>	60
3.2.1	State of the art of research on flow patterns.....	61
3.2.2	Velocity profiles	64
3.2.3	Concentration profiles.....	66
3.2.4	Critical deposition velocity	67
3.2.5	Theoretical determination of flow patterns	70
3.3	<i>Pressure drop</i>	70
3.3.1	Isothermal, stationary, homogeneous ice-slurry flow	71
3.3.2	State of the art of ice-slurry pressure drops.....	73
3.3.3	Friction factor for laminar flow	74
3.3.4	Semi-empirical correlations for the turbulent ice-slurry friction factor	74
3.3.5	General empirical determination of the friction factor for ice-slurries	75
3.3.6	Pressure drops of ice-slurry flows in heat exchangers	77
3.4	<i>Time-dependent behaviour</i>	78
	<i>Literature cited in Chapter 3</i>	79
4.	Thermodynamics and Heat Transfer	83
4.1	<i>Overview</i>	83
4.2	<i>Basic definitions</i>	83
4.2.1	Effective enthalpy and effective specific heat	83
4.2.2	Effective thermal conductivity	84
4.2.3	Dimensionless numbers	85
4.2.4	Reference temperatures and heat transfer coefficients	86
4.3	<i>Measurement techniques</i>	87
4.3.1	Introductory remarks	87
4.3.2	Local ice fraction	87
4.3.3	Local ice slurry temperature	88
4.3.4	Local ice slurry velocity	88
4.4	<i>Flow phenomena</i>	89
4.4.1	Velocity profile, mean velocity	89
4.4.2	Temperature profile, mean temperature in vertical channels	92
4.4.3	Local ice fraction profiles	93
4.5	<i>Heat transfer phenomena</i>	94
4.5.1	A brief introduction	94

4.5.2	Pipes	95
4.5.3	Heat transfer in rectangular channels	105
4.5.4	Heat transfer in rectangular channels with a bend	113
4.6	<i>Heat exchangers with stagnant flow</i>	115
4.7	<i>Industrial heat exchangers</i>	117
4.7.1	Brief introduction	117
4.7.2	Heat transfer correlations in compact heat exchangers	117
4.8	<i>Conclusions and outlook</i>	120
	<i>Literature cited in Chapter 4</i>	121
5.	Ice Slurry Production	125
5.1	<i>Fundamentals of ice slurry generation</i>	125
5.1.1	Ice crystallization	125
5.1.2	Heat and mass transfer aspects	126
5.1.3	Categories of ice slurry generator	126
5.2	<i>Current and possible methods of ice slurry production</i>	128
5.2.1	Scraped surface ice slurry generator	128
5.2.2	Vacuum ice	137
5.2.3	Direct contact generators with immiscible refrigerant	139
5.2.4	Direct contact generators with immiscible liquid secondary refrigerant	142
5.2.5	Supercooled brine method	143
5.2.6	Hydro-scraped ice slurry generator	146
5.2.7	Special coating of generator surface to avoid ice sticking to surface	147
5.2.8	Fluidized bed crystallizer	152
5.2.9	High pressure ice slurry generator	154
5.2.10	Recuperative ice making	158
	<i>Literature cited in Chapter 5</i>	161
6.	Transport	167
6.1	<i>Advantage of transport characteristics of ice slurries over conventional fluids</i>	167
6.2	<i>Design of transport systems</i>	167
6.2.1	General considerations	167
6.2.2	Single-tube versus dual-tube systems	168
6.2.3	Considerations of defrosting	168
6.2.4	Pipe Materials	170
6.2.5	Calculation of pressure drops	170
6.2.6	Avoidance and influence of phase separation	170
6.3	<i>Transport capacity</i>	174
6.3.1	Calculation of transport capacity	174
6.3.2	Pipe selection chart	175
6.4	<i>Pumping</i>	176
6.4.1	Centrifugal pumps and their application ranges	176
6.4.2	Other pumps for ice slurry	181
6.4.3	Calculation guidelines using manufacturer's data	185
6.4.4	Long term performance test	189
6.4.5	Internal build up of ice clusters in centrifugal pumps	190
6.4.6	Corrosion and Erosion	191

6.4.7 Problems at standstill	191
6.5 Fittings and related pressure loss coefficients	192
6.5.1 Test rig set up	192
6.5.2 Design of pressure taps	193
6.5.3 Data treatment	193
6.5.4 Experiments and results	195
6.5.5 Comparison of measured values of ice slurries and single phase fluids	198
6.6 Valves	199
6.7 Insulation	199
6.8 Critical conditions	199
6.9 Quick guide to ice slurry installation and operation in order to avoid blockage	200
6.9.1 Homogeneously mixed storage	200
6.9.2 Transport system	200
Literature cited in Chapter 6	201
 7. Storing/Melting and Mixing	 203
7.1 Storing vessels	203
7.1.1 Storing methods/devices and processes	203
7.1.2 Melting methods/devices and processes	206
7.2 Mixing tanks	207
7.2.1 Mixing methods/devices and processes	207
7.2.2 Stratification in mixing tanks	208
7.2.3 Power consumption in Newtonian range	209
7.2.4 Power consumption for highly-viscous range	209
7.3 Numerical modelling for storage tank design	209
7.3.1 Physical modelling of accumulation/piling and melting	209
7.3.2 Mathematical modelling	211
7.3.3 Confirmation of modelling	215
7.4 Numerical modelling for mixing tank design	219
7.4.1 Physical modelling of flow and stratification	219
7.4.2 Mathematical modelling	220
7.4.3 Confirmation of modelling	220
Literature cited in Chapter 7	221
 8. Melting Ice Slurry in Heat Exchangers.....	 223
8.1 Plate heat exchangers	223
8.1.1 Test rig set up	225
8.1.2 Measuring equipment	227
8.1.3 Heat transfer results	227
8.1.4 Correlation for heat transfer	229
8.1.5 Pressure drop results	231
8.1.6 Correlation for pressure drop	232
8.1.7 Observations	233
8.1.8 Minimum flow rate	234
8.2 Air coolers	235
8.2.1 Test rig set up	236
8.2.2 Heat transfer results	237

8.2.3	Correlation for heat transfer	239
8.2.4	Pressure drop results	239
8.2.5	Correlation for pressure drop	240
8.2.6	Comparison between single-phase media and ice slurry	242
8.2.7	Minimum flow rate	243
8.3	<i>Observations</i>	244
8.4	<i>Conclusions</i>	248
	<i>Literature cited in Chapter 8</i>	249
9.	Direct Contact Chilling and Freezing of Foods in Ice Slurries	251
9.1	<i>State of the art and conventional modes of food refrigeration</i>	251
9.2	<i>Unfreezable liquids and pumpable ice slurries as refrigerating media and fluidizing agents</i>	253
9.3	<i>Cooling of fish with ice slurries</i>	259
9.4	<i>Ice-slurry-based cooling of fruits and vegetables</i>	263
	<i>Literature cited in Chapter 9</i>	269
10.	The Control of Ice Slurry Systems	273
10.1	<i>Introduction</i>	273
10.2	<i>General organization of an ice slurry system</i>	273
10.3	<i>What is to be controlled</i>	274
10.3.1	Control of consumer units	274
10.3.2	Control of the storage tank	276
10.3.3	Control of the ice slurry generator	276
10.3.4	Control of the primary refrigerating unit	280
10.4	<i>Influence of the temperature and solute concentration on the control parameters</i>	280
10.5	<i>Consequences of the uncertainty about the ice concentration on the control of the system</i>	283
10.6	<i>Conclusions</i>	285
	<i>Literature cited in Chapter 10</i>	285
11.	Optimization of Ice Slurry systems	287
11.1	<i>Criteria</i>	287
11.2	<i>Methods</i>	288
	<i>Literature cited in Chapter 11</i>	289
12.	Present and Future Applications	291
12.1	<i>Introduction</i>	291
12.2	<i>Comfort cooling</i>	291
12.2.1	Comfort cooling of buildings	291
12.2.2	Applications to office building	292
12.2.3	Applications to institutional buildings	297
12.2.4	Applications to commercial buildings	299
12.2.5	Mine cooling	301

12.3 Food processing	302
12.3.1 Rapid cooling of vegetables	302
12.3.2 Fish processing	302
12.3.3 Meat processing	305
12.3.4 Dairy processing	305
12.3.5 Brewery	306
12.3.6 Retail food applications	308
12.4 Possible future applications	311
12.4.1 Ice pigging	311
12.4.2 Medical applications	311
12.4.3 Artificial snow	311
12.4.4 Transport refrigeration	312
12.4.5 The use of ice slurry for fire fighting	313
12.5 Conclusions	313
Literature cited in Chapter 12	314
 13. Conclusions and recommendations for further R&D	317
 Appendix 1: List of authors	321
Appendix 2: List of selected plants	325
Appendix 3: List of symbols	345
Appendix 4: List of figures	351
Appendix 5: List of tables	361