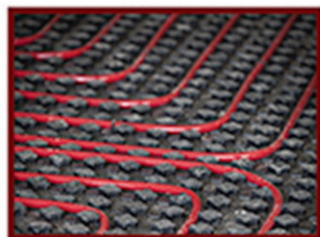
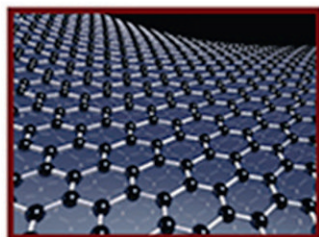


THERMAL ENERGY STORAGE TECHNOLOGIES FOR SUSTAINABILITY

SYSTEMS DESIGN, ASSESSMENT AND APPLICATIONS



S. KALAISELVAM AND R. PARAMESHWARAN



Thermal Energy Storage Technologies for Sustainability

This page intentionally left blank

Thermal Energy Storage Technologies for Sustainability

Systems Design, Assessment and Applications

by

S. Kalaiselvam

*Department of Mechanical Engineering, Anna University,
Chennai – 600 025, India*

R. Parameshwaran

*Department of Mechanical Engineering, Centre for Nanoscience and
Technology, Anna University, Chennai – 600 025, India*



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Academic Press is an imprint of Elsevier



Academic Press is an imprint of Elsevier
32 Jamestown Road, London NW1 7BY, UK
525 B Street, Suite 1800, San Diego, CA 92101-4495, USA
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK

Copyright © 2014 Elsevier Inc. 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

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK: phone (+44) (0) 1865 843830; fax (+44) (0) 1865 853333; email: permissions@elsevier.com. Alternatively you can submit your request online by visiting the Elsevier web site at <http://elsevier.com/locate/permissions>, and selecting Obtaining permission to use Elsevier material.

Notice

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. Because of rapid advances in the medical sciences, in particular, independent verification of diagnoses and drug dosages should be made.

Library of Congress Cataloging-in-Publication Data

Kalaiselvam, S.

Thermal energy storage technologies for sustainability: systems design, assessment, and applications/by S. Kalaiselvam, R. Parameshwaran. – First edition.

pages cm

Includes index.

ISBN 978-0-12-417291-3

1. Heat storage devices. 2. Heat storage. I. Parameshwaran, R. II. Title.

TJ260.K255 2014

621.402'8--dc23

2014011943

British Library Cataloguing in Publication Data

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

For information on all **Academic Press** publications
visit our web site at store.elsevier.com

Printed and bound in USA

ISBN: 978-0-12-417291-3

		Working together to grow libraries in developing countries
www.elsevier.com • www.bookaid.org		

Contents

Acknowledgments.....	xi
Preface.....	xiii
CHAPTER 1 Energy and Energy Management.....	1
1.1 Introduction	1
1.2 Energy Resources, Energy Sources, and Energy Production	1
1.3 Global Energy Demand and Consumption.....	5
1.4 Need for the Energy Efficiency, Energy Conservation, and Management.....	11
1.5 Concise Remarks.....	18
References	19
CHAPTER 2 Energy Storage.....	21
2.1 Introduction	21
2.2 Significance of Energy Storage	21
2.3 Types of Energy Storage	22
2.4 Energy Storage by Mechanical Medium	23
2.4.1 Flywheels (Kinetic Energy Storage)	23
2.4.2 Pumped Hydroelectric Storage (Potential Energy Storage).....	25
2.4.3 Compressed Air Energy Storage (Potential Energy Storage).....	26
2.5 Energy Storage by Chemical Medium	28
2.5.1 Electrochemical Energy Storage	28
2.6 Energy Storage by Electrical Medium	31
2.6.1 Electrostatic Energy Storage	31
2.7 Energy Storage by Magnetic Medium.....	33
2.7.1 Superconducting Magnetic Energy Storage	33
2.8 Energy Storage by Hydrogen Medium.....	34
2.8.1 Hydrogen-Based Fuel Cells.....	34
2.8.2 Solar Hydrogen Production.....	35
2.9 Energy Storage by Biological Medium	36
2.10 Thermal Energy Storage.....	36
2.10.1 Low Temperature Thermal Storage.....	37
2.10.2 Medium and High Temperature Thermal Storage.....	37
2.11 Technical Evaluation and Comparison of Energy Storage Technologies.....	38
2.12 Concise Remarks	52
References	52

CHAPTER 3 Thermal Energy Storage Technologies	57
3.1 Introduction	57
3.2 Thermal Energy Storage.....	57
3.2.1 Aspects of TES.....	58
3.2.2 Need for TES.....	59
3.2.3 Energy Redistribution Requirements	59
3.3 Types of TES Technologies.....	60
3.3.1 Sensible TES	60
3.3.2 Latent TES.....	60
3.3.3 Thermochemical Energy Storage	61
3.4 Comparison of TES Technologies.....	62
3.5 Concise Remarks	64
References.....	64
CHAPTER 4 Sensible Thermal Energy Storage	65
4.1 Introduction	65
4.2 Sensible Heat Storage Materials.....	65
4.2.1 Solid Storage Materials	65
4.2.2 Liquid Storage Materials	66
4.3 Selection of Materials and Methodology	66
4.3.1 Short-Term Sensible Thermal Storage	67
4.3.2 Long-Term Sensible Thermal Storage	68
4.4 Properties of Sensible Heat Storage Materials	69
4.5 STES Technologies	69
4.5.1 Storage Tanks Using Water	69
4.5.2 Rock Bed Thermal Storage	71
4.5.3 Solar Pond/Lake Thermal Storage	72
4.5.4 Building Structure Thermal Storage.....	73
4.5.5 Passive Solar Heating Storage.....	75
4.5.6 Active Solar Heating Storage	76
4.6 High Temperature Sensible Thermal Storage	77
4.7 Concise Remarks	81
References.....	81
CHAPTER 5 Latent Thermal Energy Storage	83
5.1 Introduction	83
5.2 Physics of LTES	83
5.3 Types of LTES	85
5.4 Properties of Latent Heat Storage Materials	86
5.5 Encapsulation Techniques of LTES (PCM) Materials	86
5.5.1 Direct Impregnation Method	87

5.5.2	Microencapsulation Method.....	87
5.5.3	Shape Stabilization of the PCM.....	88
5.6	Performance Assessment of LTES System in Buildings.....	89
5.7	Passive LTES Systems.....	94
5.7.1	PCM Impregnated Structures into Building Fabric Components.....	94
5.7.2	PCM Impregnated into Building Fabrics	97
5.7.3	PCM Integrated into Building Glazing Structures	100
5.7.4	PCM Color Coatings	101
5.8	Active LTES Systems	102
5.8.1	Free Cooling with the PCM TES	102
5.8.2	Comfort Cooling with the PCM TES.....	108
5.8.3	Ice-Cool Thermal Energy Storage.....	111
5.8.4	Chilled Water-PCM cool TES	115
5.9	Merits and Limitations	118
5.9.1	Merits of LTES Materials.....	118
5.9.2	Limitations of LTES Materials.....	122
5.9.3	Merits of LTES Systems.....	122
5.9.4	Limitations of LTES Systems.....	123
5.10	Summary.....	123
	References.....	124
CHAPTER 6	Thermochemical Energy Storage	127
6.1	Introduction	127
6.2	Phenomena of Thermochemical Energy Storage	127
6.3	Thermochemical Energy Storage Principles and Materials	128
6.4	Thermochemical Energy Storage Systems.....	130
6.4.1	Open Adsorption Energy Storage System.....	131
6.4.2	Closed Adsorption Energy Storage System	134
6.4.3	Closed Absorption Energy Storage System	135
6.4.4	Solid/Gas Thermochemical Energy Storage System.....	136
6.4.5	Thermochemical Accumulator Energy Storage System	137
6.4.6	Floor Heating System using Thermochemical Energy Storage	138
6.4.7	Thermochemical Energy Storage for Building Heating Applications	140
6.5	Concise Remarks	142
	References.....	144
CHAPTER 7	Seasonal Thermal Energy Storage	145
7.1	Introduction	145
7.2	Seasonal (Source) TES Technologies.....	145
7.2.1	Aquifer Thermal Storage.....	146
7.2.2	Borehole Thermal Storage.....	150

7.2.3	Cavern Thermal Storage.....	152
7.2.4	Earth-to-Air Thermal Storage	155
7.2.5	Energy Piles Thermal Storage.....	156
7.2.6	Sea Water Thermal Storage.....	156
7.2.7	Rock Thermal Storage.....	157
7.2.8	Roof Pond Thermal Storage.....	157
7.3	Concise Remarks	158
	References.....	161
CHAPTER 8	Nanotechnology in Thermal Energy Storage	163
8.1	Introduction	163
8.2	Nanostructured Materials	163
8.2.1	Preparation and Characterization of Nanomaterials.....	163
8.2.2	Hybrid Nanomaterials	167
8.3	Nanomaterials Embedded Latent Heat Storage Materials	174
8.3.1	Evaluation of Thermal Storage Properties	175
8.4	Merits And Challenges.....	189
8.5	Concise Remarks	191
	References.....	192
CHAPTER 9	Sustainable Thermal Energy Storage	203
9.1	Introduction	203
9.2	Sustainable Thermal Storage Systems	203
9.2.1	Low Energy Thermal Storage	203
9.2.2	Low Carbon Thermal Storage	204
9.2.3	Geothermal Energy Storage	216
9.2.4	Wind-Thermal-Cold Energy Storage.....	222
9.2.5	Hybrid TES	223
9.2.6	CHP Thermal Storage	223
9.3	Leadership in Energy and Environmental Design (LEED) and Sustainability Prospects.....	227
9.4	Concise Remarks	232
	References.....	233
CHAPTER 10	Thermal Energy Storage Systems Design.....	237
10.1	Introduction	237
10.2	Sensible Heat Storage Systems	237
10.3	Latent Heat Storage Systems.....	238
10.3.1	Sizing of ITES System	238
10.3.2	Sizing of Chilled Water Packed Bed LTES System	239
10.4	Design Examples	241
10.4.1	Long-Term Thermal Storage Option.....	241
10.4.2	Short-Term Thermal Storage Option.....	242

10.4.3	Short-Term Thermal Storage Option in Piping Systems.....	242
10.4.4	Heating Thermal Storage Option with Pressurized Water Systems	243
10.4.5	TES Option with Waste Heat Recovery	244
10.5	Concise Remarks	244
	Further Reading	245
CHAPTER 11 Review on the Modeling and Simulation of Thermal Energy Storage Systems.....		247
11.1	Introduction	247
11.2	Analytical/Numerical Modeling and Simulation.....	247
11.2.1	Latent Thermal Energy Storage	247
11.3	Configurations-Based Model Collections.....	256
11.4	Modeling and Simulation Analysis	261
11.4.1	Numerical Solution and Validation	261
11.4.2	Materials Selection and Configuration.....	266
11.4.3	Economic Perspectives.....	266
11.5	Concise Remarks	266
	References.....	267
CHAPTER 12 Assessment of Thermal Energy Storage Systems		279
12.1	Introduction	279
12.2	Evaluation of Thermal Storage Properties.....	279
12.3	Energy and Exergy Concepts	281
12.3.1	Distinction between Energy and Exergy	281
12.3.2	Quality Concepts	285
12.3.3	Exergy in Performance Assessment of Thermal Storage Systems.....	286
12.3.4	Exergy and the Environment	288
12.4	Concise Remarks	307
	References.....	307
CHAPTER 13 Control and Optimization of Thermal Energy Storage Systems		311
13.1	Introduction	311
13.2	Control Systems and Methodologies.....	311
13.2.1	Types of Control Methodologies	313
13.2.2	Control Methodology of Thermal Storage Systems.....	316
13.3	Optimization of Thermal Storage Systems.....	326
13.3.1	Thermoeconomic Optimization.....	330
13.3.2	Multiobjective Optimization	336
13.4	Concise Remarks	342
	References.....	343