Contents

About the Editors XV
List of Contributors XVII
IEA Solar Heating and Cooling Programme XXI
Acknowledgments XXIII

Part I 1

1 Principles 3
Markus Peter
1.1 Introduction 3
1.2 Solar Irradiance in Technical Applications 6
1.3 Quantifying Useful Solar Irradiation 6
1.4 Solar Thermal Applications 7
1.5 Calculating the Solar Contribution 10
1.6 Conclusions 10

2 Solar Thermal Market 13
Karl-Anders Weiß, Christoph Zauner, Jay Burch, and Sandrin Saile
2.1 Introduction 13
2.2 Collector Types 14
2.2.1 Unglazed Collectors 14
2.2.2 Flat Plate Collectors (FPC) 15
2.2.3 Evacuated Flat Plate Collector (EFPC) 16
2.2.4 Evacuated Tube Collectors (ETC) 16
2.2.5 Concentrating Collectors 16
2.2.6 Air Collectors 18
2.2.7 Market Share of Different Collector Types 18
2.3 Regional Markets 19
2.4 Market Trends 22
2.4.1 Global Market Development 22
2.4.2 Global Market Forecast 25
2.4.3 Focus on Europe 25
Links Providing Updated Market Data and Forecasts 26
References 26
3 Thermal Solar Energy for Polymer Experts 29
Philippe Papillon and Claudius Wilhelms

3.1 Solar Thermal Systems and Technical Requirements 29

3.2 Overview of Solar Thermal Applications 29
3.2.1 Swimming Pool Heating Applications 31
3.2.2 Domestic Hot Water Preparation for Single Family Houses 33
3.2.3 Domestic Hot Water Preparation for Multi-family Houses 39
3.2.4 Space Heating and DHW Preparation 40
3.2.5 Solar Cooling Applications 44
3.2.6 Solar Assisted District Heating 47
3.2.7 Process Heat Applications 49

3.3 Solar Thermal Collectors 50
3.3.1 Basic Principle of a Solar Thermal Collector 50
3.3.2 Unglazed Collector 53
3.3.3 Glazed Flat Plate Collector 56
3.3.4 Evacuated Tubes 58
3.3.5 Other Types of Collectors 60
3.3.6 Selective Coatings for Solar Absorbers 62

3.4 Small to Medium Size Storages 63
3.4.1 Classification of Heat Storages 64
3.4.2 Domestic Hot Water Storages 65
3.4.3 Non-domestic Hot Water Storages 67
3.4.4 Non-water Based Storage 68

3.5 Sources of Further Information 70
3.5.1 Related International Energy Agency Solar Heating and Cooling Tasks 70
3.5.2 Web Sites and Projects Related to Solar Thermal Systems 70

References 70

4 Conventional Collectors, Heat Stores, and Coatings 73
Stephan Fischer, Harald Drück, Stephan Bachmann, Elke Streicher, Jens Ullmann, and Beate Traub

4.1 Collectors 73
4.1.1 Transparent Covers 75
4.1.2 Absorber Plate Risers and Manifolds 75
4.1.3 Absorber Coatings 76
4.1.4 Thermal Insulation 77

4.2 Material Properties of Insulations 79
4.2.1 Casing 80
4.2.2 Sealing 80
4.2.3 Collector Mounting Structures 80

4.3 Heat Store 81
4.4 Other Components 84

4.5 Analysis of Typical Combsystems 86
4.5.1 Combsystems Analyzed 86
4.5.2 Weight of the Components 86
4.5.3 Materials Used in the Systems 86
4.5.4 Materials Used in the Components 88
4.6 Definition of Polymeric Based Solar Thermal Systems 92
4.7 Life Cycle Assessment Based on Cumulated Energy Demand, Energy
Payback Time, and Overall Energy Savings 97
4.8 Cumulated Energy Demand, Energy Payback Time, and Overall
Energy Savings for Conventional and Polymeric Based Domestic
Hot Water Systems 98
4.8.1 System Boundary 100
4.8.2 Cumulative Energy Demand 100
4.8.2.1 Cumulative Energy Demand for Production 100
4.8.3 Conventional Reference System for the Determination of the
Primary Energy Saved by the Solar Thermal System 101
4.8.4 Fractional Energy Savings 102
4.8.5 Lifetime 102
4.8.6 Calculation for Solar Domestic Hot Water Systems 102
4.8.6.1 Materials and Masses of the Systems Used for the
Reference System (DHW1) 102
4.8.6.2 Materials and Masses of the Systems Used for the Polymeric
System (DHW2) 102
4.8.6.3 Input Values and Results for Determination of the CED 102
4.8.6.4 Overall Energy Savings and Energy Payback Time 104
References 106

5 Thermal Loads on Solar Collectors and Options for their Reduction 107
Christoph Reiter, Christoph Trinkl, and Wilfried Zörner
5.1 Introduction 107
5.2 Results of Monitoring Temperature Loads 107
5.3 Measures for Reduction of the Temperature Loads 114
References 117

6 Standards, Performance Tests of Solar Thermal Systems 119
Stephan Fischer and Christoph Zimmermann
6.1 Introduction 119
6.2 Collectors 119
6.2.1 Testing of Solar Collectors for Durability and Reliability 120
6.2.2 Testing of Solar Collectors for Thermal Performance 120
6.3 Solar Thermal Systems 121
6.3.1 Testing of Solar Thermal Products 124
6.3.1.1 CSTG Method 125
6.3.1.2 DST Method 125
6.3.2 CTSS Method 125
6.4 Conclusion 125
Part II 127

7  Plastics Market 129
Katharina Resch and Gernot M. Wallner
References 134

8  Polymeric Materials 135
Gernot M. Wallner, Reinhold W. Lang, and Karl Schnetzinger
8.1 Introduction 135
8.2 Material Structure and Morphology of Polymers 136
8.3 Inner Mobility and Thermal Transitions of Polymers 143
8.4 Polymer Additives and Compounds 146
8.4.1 Stabilizing Additives 147
8.4.2 Antioxidants 147
8.4.3 Light Stabilizers 148
8.4.4 Modifying Additives 148
References 149

9  Processing 151
9.1 Structural Polymeric Materials 151
Helmut Vogel
9.1.1 Introduction to Polymer Processing 151
9.1.2 Extrusion Based Processes 152
9.1.2.1 Profile Extrusion 152
9.1.2.2 Film Blowing 154
9.1.2.2.1 Cast Film Extrusion 154
9.1.2.3 Calendar Stack Process for Plates 155
9.1.2.4 Blow Molding 157
9.1.2.4.1 Extrusion Blow Molding 159
9.1.2.4.2 Injection Blow Molding 160
9.1.3 Injection Molding 161
9.1.3.1 Injection Molding Cycle 162
9.1.4 Thermoforming 164
9.1.5 Fiber Reinforced Polymer 165
9.1.5.1 Sheet Molding Compound (SMC) 165
9.1.5.2 Glass Mat Thermoplastics (GMT) 165
References 166

9.2 Paint Coatings for Polymeric Solar Absorbers and Their Applications 167
Ivan Jerman, Matjaž Koželj, Lidija Slemenik Pešte, and Boris Orel
9.2.1 Outline of Content 167
9.2.2 General Remarks about Selective Paint Coatings 168
9.2.3 Preparation of Selective Paints 169
9.2.3.1 Effect of Dispersants on Pigment Dispersions 170
9.2.3.2 Dispersants 171
9.2.3.3 Trisilanol T₇ POSS Dispersants for Colored TISS Paint Coatings 174
9.2.4 Application Techniques for Spectrally Selective Paints 175
9.2.4.1 Brush and Hand Roller Application 175
9.2.4.2 Spray Application 176
9.2.4.3 Case Study: Application of TISS Paint on a Polymeric Substrate by Using Simple Silane Dispersants 178
9.2.4.4 Direct Coating Application Techniques 179
9.2.4.5 Dip Coating 180
9.2.4.6 Dip and Flow Coating 180
9.2.4.7 Roll Coating 182
9.2.4.8 Coil Coating 182
9.2.5 Conclusions 185

10 Polymer Durability for Solar Thermal Applications 187
Susan C. Mantell and Jane H. Davidson
10.1 Introduction 187
10.2 Polymeric Glazing 188
10.3 Polymeric Absorbers and Heat Exchangers 189
10.3.1 Overview of Relevant Polymer Material Properties and Requirements 191
10.3.2 Additional Material Considerations 196
10.3.2.1 Fillers to Improve Thermal Conductivity and Strength 196
10.3.2.2 Scaling 198
10.3.2.3 Oxidation 199
10.3.3 Absorbers 201
10.3.3.1 Material Selection 201
10.3.4 Heat Exchangers 204
10.3.4.1 Material Selection 205
10.3.4.2 Polymer Heat Exchanger Applications 205
10.4 Conclusion 206
References 207

11 Plastics Properties and Material Selection 211
Ulrich Endemann and Andreas Mägerlein
11.1 Introduction 211
11.2 How to Select the Right Material 211
11.3 Material Databases 212
11.4 Selection Criteria 213
11.5 Real Life Example: Standard Collector in Plastic (1:1 Substitution) 213
11.5.1 Preselection 214
11.5.1.1 Housing 215
11.5.1.2 Absorber 216
11.5.1.3 Sealing 217
11.5.1.4 Glazing 217
11.5.1.5 Insulation 217
11.6 Summary 218

Part III 219

12 State of the Art: Polymeric Materials in Solar Thermal Applications 221
Michaela Meir, Fabian Ochs, Claudius Wilhelms, and Gernot Wallner
12.1 Solar Collectors 221
12.1.1 Pool Absorbers 221
12.1.2 Material Substitution in Conventional Collector Designs 222
12.1.3 Glazed Flat-Plate Collectors with Polymeric Absorbers 224
12.1.4 Air Collector Systems 224
12.1.5 Integrated Storage Collectors and Thermosiphon Systems 225
12.1.6 Collector Glazing 227
12.1.7 Integrated and Multifunctional Applications 228
12.1.8 Absorber Designs from a Polymer Engineering Point of View 229
12.1.9 Summary 231
12.2 Small to Mid-Sized Polymeric Heat Stores 231
12.2.1 Introduction 231
12.2.2 Challenges 235
12.3 Polymeric Liners for Seasonal Thermal Energy Stores 235
12.3.1 Envelope Design of Thermal Energy Stores 236
12.3.2 Liner of Pilot and Research Thermal Energy Stores 237
12.3.3 Summary 239
References 241

13.1 Structural Polymeric Materials – Aging Behavior of Solar Absorber Materials 243
Suanne Kahlen, Gernot M. Wallner, and Reinhold W. Lang
13.1.1 Introduction and Scope 243
13.1.2 Methodology 244
13.1.3 Results, Discussion, and Outlook 246
13.1.3.1 Characterization of Physical and Chemical Aging of Polymeric Solar Materials by Mechanical Testing 246
13.1.3.2 Aging Behavior of Polymeric Solar Absorber Materials – Part 1: Engineering Plastics 247
13.1.3.3 Aging Behavior of Polymeric Solar Absorber Materials – Part 2: Commodity Plastics 248
13.1.3.4 Aging Behavior and Lifetime Modeling for Polymeric Solar Absorber Materials 249
13.1.3.5 Aging Behavior of Polymeric Solar Absorber Materials: Aging on Component Level 250
References 252
13.2 Thermotropic Layers for Overheating Protection of all-Polymeric Flat Plate Solar Collectors 255
Katharina Resch, Robert Hausner, Gernot M. Wallner, and Reinhold W. Lang

13.2.1 Introduction 255
13.2.2 Materials and Sample Preparation 256
13.2.3 Physical Characterization of the Polymers 257
13.2.4 Results and Discussion 258
13.2.5 Effect of Thermotropic Layers on Collector Efficiency and Stagnation Temperatures 262
13.2.6 Outlook 263

References 264

13.3 Application of POSS Compounds for Modification of the Wetting Properties of TISS Paint Coatings 267
Ivan Jerman, Boris Orel, and Matjaž Kočelj

13.3.1 Introduction 267
13.3.2 Wetting of Surfaces 270
13.3.2.1 Basic Principles – Learning from Nature 270
13.3.2.2 Surface Energy 272
13.3.2.3 Surface Roughness 273
13.3.2.4 Morphology of TISS Paint Coatings 275
13.3.3 POSS Nanocomposites as Low Surface Energy Additives for Coatings 276
13.3.3.1 Synthesis and Structural Characteristics of POSS Molecules 276
13.3.4 Anti-wetting Properties of Coatings with Smooth Surfaces – Lacquers for Polymeric Glazing 278
13.3.4.1 Structure of Fluoropolymer Resin Binders – General Remarks 279
13.3.4.2 Contact Angles and Surface Properties of Lumiflon Resin Binders 280
13.3.4.3 Interaction of POSS – SEM Micrographs and Optical Transmission 281
13.3.5 Anti-wetting Properties of Coatings on Rough Surfaces – TISS Paint Coatings 282
13.3.5.1 Wetting Properties of TISS Coatings 282
13.3.6 Conclusions 284

References 284

14 Conceptual Design of Collectors 287
Karl-Anders Weiss, Steffen Jack, Axel Müller, and John Rekstad

14.1 Introduction 287
14.2 Calculation of Collector Efficiency 287
14.3 Flow Optimization 291
14.4 Optimization of the Fluid Dynamics in Polymeric Collectors 291
14.4.1 Optimization of the Absorber 291
14.4.2 Optimization of the Fluid Dynamics in the Header 292
14.4.3 Optimization of the Fluid Dynamics Non-rectangular Collectors 292
14.5 Collector Mechanics 295


15  **Collectors and Heat Stores**  301  
*Stefan Brunold, Philippe Papillon, Micha Plaschkes, John Rekstad, and Claudius Wilhelms*

15.1 Introduction  301
15.2 Solar Absorber Made of High-Performance Plastics  301
15.2.1 General Presentation  301
15.2.2 Detailed Description  302
15.2.3 Experiences with Development of the Products  307
15.3 Flate Plate Collector with Overheating Protection  307
15.3.1 General Presentation  307
15.3.2 Detailed Description  307
15.3.3 Experience Gained with Development of the Products  309
15.4 Flat Plate Collectors with a Thermotropic Layer  310
15.4.1 General Presentation  310
15.4.2 Detailed Description  310
15.4.3 Experience Gained with Development of the Products  313
15.5 Solar Storage Tank with Polymeric Sealing Technology with Storage Volumes from 2 to 100 m$^3$  313
15.5.1 General Presentation  313
15.5.2 Detailed Description  314
15.5.3 Experience Gained with Development of the Products  314

References  317

16  **Durability Tests of Polymeric Components**  319  
*Stefan Brunold, Florian Ruesch, Roman Kunic, John Rekstad Michaela Meir, and Claudius Wilhelms*

16.1 Introduction  319
16.2 Twenty Years Outdoor Weathering of Polymeric Materials for use as Collector Glazing  320
16.2.1 Introduction  320
16.2.2 Material Selection  320
16.2.3 Exposure  321
16.2.4 Evaluation of Optical Properties  322
16.2.5 Results  323
16.2.5.1 PMMA  323
16.2.5.2 PC  325
16.2.5.3 Fluoropolymers  326
16.2.5.4 UP  329
16.2.5.5 PET and PVC  330
16.2.6 Conclusion  330
16.3 Accelerated Lifetime Testing of a Polymeric Absorber Coating  332
16.3.1 Introduction  332
16.3.2 Application of the ALT Test Procedure on the TISS Painted Absorber 333
16.3.3 Adaption of the ALT Procedure to the TISS Painted Absorber 333
16.3.4 Conclusions 337

16.4 Evaluation of Temperature Resistance of a Polymer Absorber in a Solar Collector 337
16.4.1 Background 337
16.4.2 Method 338
16.4.3 Experiments 339
16.4.4 Service Life for a Plastics Absorber Made in PPS 341
16.4.5 Conclusion 343

16.5 Determination of Water Vapor Transport through Polymeric Materials at Raised Temperatures 343
16.5.1 Measurement Setup/Testing Rig 344
16.5.2 Results 346
16.5.3 Conclusion 347
References 347

17 Architecturally Appealing Solar Thermal Systems – A Marketing Tool in Order to Attract New Customers and Market Segments 351
Ingvild Skjelland, John Rekstad, Karl-Anders Weiss, and Maria Christina Munari Probst
17.1 Introduction 351
17.2 Architectural Integration as a Marketing Tool 351
17.3 Web Database 353
17.4 Examples 354
References 357

18 Obstacles for the Application of Current Standards 359
Stephan Fischer, Christoph Zauner, Philippe Papillon, Andreas Bohren, Stefan Brunold, and Robert Hausner
18.1 Introduction 359
18.2 Internal Absorber Pressure Test 359
18.2.1 Description of the Specific Test and Test Procedure 359
18.2.2 Why this is a Problem for Polymeric Collectors or Why this Test does not Reflect the Requirements for Polymeric Collectors 360
18.2.3 Possible Alternative Procedure 360
18.3 High-Temperature Resistance and Exposure Tests 360
18.3.1 Description of the Specific Test and Test Procedure 360
18.3.2 Why this is a Problem for Polymeric Collectors or Why this Test does not Reflect the Requirements for Polymeric Collectors 361
18.3.3 Possible Alternative Procedure 361
18.3.3.1 General Comments 361
18.3.3.2 Comments on Overheating Protection 362
18.3.3.3 Passive Devices 362
18.3.3.4 Active Devices 363
18.4 Mechanical Load Test 363
18.4.1 Description of the Specific Test and Test Procedure 363
18.4.2 Why this is a Problem for Polymeric Collectors or Why this Test does not Reflect the Requirements for Polymeric Collectors 364
18.4.2.1 Typical Data for Snow Load (According to EN12975 and to PV Norms such as EN61646 etc.) 364
18.4.2.2 Typical Data for Wind Load (According to EN12975 and to PV Norms such as EN61646 etc.) 364
18.4.2.3 Typical Normative Requirements 364
18.4.3 Possible Alternative Procedure 365
18.5 Impact Resistance Test 365
18.5.1 Description of the Specific Test and Test Procedure 365
18.5.2 Why this is a Problem for Polymeric Collectors or Why this Test does not Reflect the Requirements for Polymeric Collectors 365
18.5.2.1 Typical Data for Steel Ball Test of 150 g (According to EN12975) 366
18.5.2.2 Typical Data for Ice Stones Test of Different Sizes (According to EN12975 and to PV Norms such as EN61646 etc.) 366
18.5.2.3 Typical Normative Requirements 366
18.5.3 Possible Alternative Procedure 366
18.6 Discontinuous Efficiency Curves 366
18.6.1 Description of the Specific Test and Test Procedure 366
18.6.2 Problems Regarding Polymeric Collectors 367
18.6.2.1 The Limit is Dependent Mainly on the Absorber Temperature 367
18.6.2.2 The Limit is Dependent on the Absorber Temperature and on the Ambient Temperature 367
18.6.3 Possible Alternative Procedures 368
18.6.3.1 Determination of the Validity Limit for the Standard Procedures 368
18.6.3.2 Determination of Stagnation Temperature 369
Reference 370

Glossary 371

Polymeric Materials 371
Abbreviations 371
Terms and Definitions 372
Solar Thermal Systems 379
Abbreviations 379
Terms and Definitions 379

Index 385