Contents

1	**State of the Art of Microreaction Technology**	1
1.1	Definition	1
1.1.1	Microsystems Termed Microreactor	1
1.1.2	Structural Hierarchy of Microreactors	1
1.1.3	Functional Classification of Microreactors	4
1.1.4	Dividing Line Between Analysis and Reaction Systems	4
1.2	Fundamental Advantages of Microreactors	5
1.2.1	Fundamental Advantages of Miniaturized Analysis Systems	5
1.2.2	Fundamental Advantages of Nano-Scale Reactors	5
1.2.3	Advantages of Microreactors Due to Decrease of Physical Size	6
1.2.4	Advantages of Microreactors Due to Increase of Number of Units	8
1.3	Potential Benefits of Microreactors Regarding Applications	10
1.4	References	12
2	**Modern Microfabrication Techniques for Microreactors**	15
2.1	Microfabrication Techniques Suitable for Microreactor Realization	15
2.2	Evaluation of Suitability of a Technique	16
2.3	Anisotropic Wet Etching of Silicon	17
2.4	Dry Etching of Silicon	19
2.5	LIGA Process	20
2.6	Injection Molding	21
2.7	Wet Chemical Etching of Glass	22
2.8	Advanced Mechanical Techniques	23
2.8.1	Surface Cutting with Diamond Tools	23
2.8.2	Milling, Turning and Drilling	23
2.8.3	Punching	24
2.8.4	Embossing	24
2.9	Isotropic Wet Chemical Etching of Metal Foils	25
2.10	Electro Discharge Machining (EDM) of Conductive Materials	26
2.10.1	Wire-Cut Erosion and Die Sinking	27
2.10.2	μ-EDM Drilling	29
2.11	Laser Micromachining	29
2.12	Interconnection Techniques	30
2.12.1	Microlamination of Thin Metal Sheets	30
2.13	Functional Coatings	33
2.13.1	Functional Coatings for Corrosion Prevention	33
2.13.2	Functional Coatings for Fouling Prevention	34
2.14	References	35

3	**Micromixers**	41
3.1	Mixing Principles and Classes of Macroscopic Mixing Equipment	41
3.2	Mixing Principles and Classes of Miniaturized Mixers	43
3.3	Potential of Miniaturized Mixers	46
3.4	Contacting of Two Substreams, e.g. in a Mixing Tee Configuration	49
3.4.1	Mixing Tee-Type Configuration	49
3.4.2	Double Mixing Tee-Type Configuration	50
3.5	Collision of High-Energy Substreams for Spraying/Atomizing	52
3.5.1	Collision of Three Substreams in a Microjet Reactor	52
3.6	Injection of Many Small Substreams of One Component into a Main Stream of Another Component	53
3.6.1	Injection of Multiple Microjets	53
3.7	Manifold Splitting and Recombination of a Stream Consisting of Two Fluid Lamellae of Both Components	55
3.7.1	Multiple Flow Splitting and Recombination Combined with Channel Reshaping	55
3.7.2	Multiple Flow Splitting and Recombination Using Fork-Like Elements	58
3.7.3	Multiple Flow Splitting and Recombination Using a Separation Plate	60
3.7.4	Multiple Flow Splitting and Recombination Using a Ramp-Like Channel Architecture	62
3.8	Injection of Many Substreams of Both Components	64
3.8.1	Multilamination of Fluid Layers in an Interdigital Channel Configuration	64
3.8.2	Vertical Multilamination of Fluid Layers Using a V-type Nozzle Array	73
3.8.3	Multilamination Using a Stack of Platelets with Microchannels	75
3.8.4	Multilamination Using a Stack of Platelets with Star-Shaped Openings	79
3.9	Decrease of Diffusion Path Perpendicular to the Flow Direction by Increase of Flow Velocity	80
3.9.1	Decrease of Layer Thickness by Hydrodynamic Focusing	80
3.10	Externally Forced Mass Transport, e.g. by Stirring, Ultrasonic Wave, Electrical and Thermal Energy	83
3.10.1	Dynamic Micromixer Using Magnetic Beads	83
3.11	References	83
4	**Micro Heat Exchangers**	87
4.1	Micro Heat Exchangers with Wide and Flat Channels	89
4.1.1	Cross-Flow Heat Exchange in Stacked Plate Devices	89
4.1.2	Cross-Flow Heat Exchange Based on Cross-Mixing	92
4.1.3	Counter-Flow Heat Exchange in Stacked Plate Devices	94
4.1.4	Electrically Heated Stacked Plate Devices	97
4.2	Micro Heat Exchangers with Narrow and Deep Channels	99
4.2.1	Heat Exchanger with One-Sided Structured Channels	99
4.2.2	Heat Exchanger with Double-Sided Structured Channels	100

4.3	Micro Heat Exchangers with Breakthrough Channels	102
4.4	Axial Heat Conduction	104
4.4.1	Numerical Calculations of the Influence of Material Choice on Heat Transfer Efficiency	104
4.4.2	The Use of Thermal Blocking Structures	105
4.5	Permanent Generation of Entrance Flow by Fins	106
4.6	Generation of a Periodic Flow Profile by Sine-Wave Microchannels	107
4.7	Microtechnology-Based Chemical Heat Pumps	108
4.8	Performance Characterization of Micro Heat Exchangers	109
4.8.1	Temperature Profiles of Micro Heat Exchangers Yielded by Thermograms of Infrared Cameras	110
4.9	References	112
5	**Microseparation Systems and Specific Analytical Modules for Microreactors**	115
5.1	Microextractors	115
5.1.1	Partially Overlapping Channels	115
5.1.2	Wedge-Shaped Flow Contactor	119
5.1.3	Contactor Microchannels Separated by a Micromachined Membrane	122
5.1.4	Contactor Microchannels Separated by Sieve-Like Walls	126
5.1.5	Micromixer–Settler Systems	126
5.2	Microfilters	130
5.2.1	Isoporous-Sieve Microfilters	131
5.2.2	Cross-Flow Microfilters	131
5.3	Gas Purification Microsystems	133
5.4	Gas Separation Microdevices	134
5.5	Specific Analytical Modules for Microreactors	136
5.5.1	Analytical Modules for In-Line IR Spectroscopy	136
5.5.2	Analytical Module for Fast Gas Chromatography	136
5.6	References	140
6	**Microsystems for Liquid Phase Reactions**	143
6.1	Types of Liquid Phase Microreactors	144
6.2	Liquid/Liquid Synthesis of a Vitamin Precursor in a Combined Mixer and Heat Exchanger Device	144
6.3	Acrylate Polymerization in Micromixers	151
6.4	Ketone Reduction Using a Grignard Reagent in Micromixers	154
6.5	Laboratory-Scale Organic Chemistry in Micromixer/Tube Reactors	158
6.6	Dushman Reaction Using Hydrodynamic Focusing Micromixers and High-Aspect Ratio Heat Exchangers	162
6.7	Synthesis of Microcrystallites in a Microtechnology-Based Continuous Segmented-Flow Tubular Reactor	164
6.8	Electrochemical Microreactors	166

6.8.1 Synthesis of 4-Methoxybenzaldehyde in a Plate-to-Plate Electrode Configuration 166
6.8.2 Scouting Potentiodynamic Operation of Closed Microcells 169
6.9 References 171

7 Microsystems for Gas Phase Reactions 173
7.1 Catalyst Supply for Microreactors 173
7.2 Types of Gas Phase Microreactors 176
7.3 Microchannel Catalyst Structures 177
7.3.1 Flow Distribution in Microchannel Catalyst Reactors 177
7.3.2 Partial Oxidation of Propene to Acrolein 178
7.3.3 Selective Partial Hydrogenation of a Cyclic Triene 180
7.3.4 H_2/O_2 Reaction 184
7.3.5 Selective Partial Hydrogenation of Benzene 186
7.3.6 Selective Oxidation of 1-Butene to Maleic Anhydride 187
7.3.7 Selective Oxidation of Ethylene to Ethylene Oxide 187
7.3.8 Reactions Utilizing Periodic Operation 188
7.4 Microsystems with Integrated Catalyst Structures and Heat Exchanger 193
7.4.1 Oxidative Dehydrogenation of Alcohols 193
7.4.2 Synthesis of Methyl Isocyanate and Various Other Hazardous Gases 197
7.4.3 H_2/O_2 Reaction in the Explosion Regime 200
7.5 Microsystems with Integrated Catalyst Structures and Mixer 203
7.5.1 Synthesis of Ethylene Oxide 203
7.6 Microsystems with Integrated Catalyst Structures, Heat Exchanger and Sensors 209
7.6.1 Oxidation of Ammonia 209
7.6.2 H_2/O_2 Reaction 214
7.7 Microsystems with Integrated Mixer, Heat Exchanger, Catalyst Structures and Sensors 217
7.7.1 HCN Synthesis via the Andrussov Process 217
7.8 References 224

8 Gas/Liquid Microreactors 229
8.1 Gas/Liquid Contacting Principles and Classes of Miniaturized Contacting Equipment 229
8.2 Contacting of Two Gas and Liquid Substreams in a Mixing Tee Configuration 232
8.2.1 Injection of One Gas and Liquid Substream 232
8.2.2 Injection of Many Gas and Liquid Substreams into One Common Channel 233
8.2.3 Injection of Many Gas and Liquid Substreams into One Packed Channel 235

8.2.4 Injection of Many Gas Substreams into One Liquid Channel with Catalytic Walls 237
8.2.5 Injection of Many Gas and Liquid Substreams into Multiple Channels 239
8.3 Generation of Thin Films in a Falling Film Microreactor 244
8.4 References 255

9 Microsystems for Energy Generation 257
9.1 Microdevices for Vaporization of Liquid Fuels 257
9.2 Microdevices for Conversion of Gaseous Fuels to Syngas by Means of Partial Oxidations 260
9.2.1 Hydrogen Generation by Partial Oxidations 260
9.2.2 Partial Oxidation of Methane in a Stacked Stainless Steel Sheet System 261
9.2.3 Partial Oxidation of Methane in a Microchannel Reactor 263
9.3 Microdevices for Conversion of Gaseous Fuels to Syngas by Means of Steam Reforming 265
9.3.1 Steam Reforming of Methanol in Microstructured Platelets 265
9.4 References 268

10 Microsystems for Catalyst and Material Screening 271
10.1 Parallel Screening of Heterogeneous Catalysts in a Microchannel Reactor 271
10.2 Parallel Screening of Heterogeneous Catalysts in Conventional Mini-Scale Reactors 274
10.3 References 276

11 Methodology for Distributed Production 277
11.1 The Miniplant Concept 277
11.1.1 Miniplant Concept for HCN Manufacture 278
11.1.2 The Disposable Batch Miniplant 279
11.2 Paradigm Change in Large-Scale Reactor Design Towards Operability and Environmental Aspects Using Miniplants 280
11.3 References 283

Index 285