Contents

. .

.

Preface ix Acknowledgments xii **Introduction to Basic Properties of Hydrogen** 1 1 Basics about the Hydrogen Element 1.1 1 Basics about the Hydrogen Molecule 1.2 3 Other Fundamental Aspects of Hydrogen 1.3 4 Safety and Precautions about Hydrogen 1.4 5 References 5 **Hydrocarbons for Hydrogen Generation** 2 7 **Basics about Hydrocarbons** 2.1 7 **Steam Methane Reforming** 2.2 8

2.3	Partial Oxidation		10
2.4	Methanol and Ethanol Steam Reforming		
2.5	Glycerol Reforming		15
	2.5.1	Glycerol Reforming Processes	15
	2.5.2	Mechanistic Aspects of Glycerol Reforming Reactions	17
	2.5.3	Catalytic Reforming of Glycerol	17
2.6	Cracking of Ammonia and Methane		18
	2.6.1	Ammonia Cracking	18
	2.6.2	Methane Cracking	22
	2.6.3	Other Decomposition Methods	23
2.7	Summary ·		24
	Refere	ences	25
			v

vi Contents

3	Solar Hydrogen Generation: Photocatalytic and Photoelectrochemical Methods 27			
	3.1	Basic	s about Solar Water Splitting	27
	3.2	Photo	catalyic Methods	28
		3.2.1	Background	28
		3.2.2	Metal Oxides	29
		3.2.3	Metal Oxynitrides/Metal Nitrides/Metal Phosphides	31
		3.2.4	Metal Chalcogenides	32
		3.2.5	Conclusion	35
	3.3 Photoel		electrochemical Methods	36
		3.3.1	Background	36
		3.3.2	Photocathode for Water Reduction	36
		3.3.3	Photoanode for Water Oxidation	40
		3.3.4	Conclusion	45
	3.4	Summ	nary	45
		Refere	ences	46
4	Bioł	nydroge	en Generation and Other Methods	51
	4.1	Basics	s about Biohydrogen	51
	4.2	Pathw	vays of Biohydrogen Production from Biomass	52
	4.3	Thern	nochemical Conversion of Biomass to Hydrogen	55
		4.3.1	Hydrogen from Biomass via Pyrolysis	55
		4.3.2	Hydrogen from Biomass via Gasification	58
		4.3.3	Hydrogen from Biomass via Supercritical Water (Fluid–Gas) Extraction	60
		4.3.4	Comparison of Thermochemical Processes	61
	4.4	Biological Process for Hydrogen Production		62
		4.4.1	Biophotolysis of Water Using Microalgae	64
		4.4.2	Photofermentation	66
		4.4.3	Dark Fermentation	66
		4.4.4	Two-Stage Process: Integration of Dark and Photofermentation	67
	4.5	Summ		69
	1.5	Refere		69
5	Esta		d Methods Based on Compression and Cryogenics	75
			Issues about Hydrogen Storage	75
			Pressure Compression	78
	5.3	-	d Hydrogen	84
	5.4	Summary		
		Refere		90

Contents Vii

.....

6	Che	mical S	Storage Based on Metal Hydrides and Hydrocarbons	91
	6.1	Basics	s on Hydrogen Storage of Metal Hydrides	91
	6.2	Hydro	ogen Storage Characteristics of Metal Hydrides	92
		6.2.1	Storage Capacities	93
		6.2.2	Thermodynamics and Reversible Storage Capacity	93
		6.2.3	Hydrogenation and Dehydrogenation Kinetics	95
		6.2.4	Cycling Stability	99
		6.2.5	Activation	99
	6.3	Differ	ent Metal Hydrides	100
		6.3.1	Binary Metal Hydrides	100
		6.3.2	Metal Alloy Hydrides	100
		6.3.3	Complex Metal Hydrides	101
		6.3.4	Improving Metal Hydride Performance	102
	6.4	Hydro	ocarbons for Hydrogen Storage	108
		6.4.1	Reaction between Carbon Atom and Hydrogen	109
		6.4.2	Reaction between Solid Carbon and Hydrogen	110
		6.4.3	Reaction between Carbon Dioxide and Hydrogen	111
	6.5	Summ	nary	115
		Refere	ences	116
7	Phy	sical St	torage Using Nanostructured and Porous Materials	121
	7.1	Physic	cal Storage Using Nanostructures	121
		7.1.1	Carbon Nanostructures	121
		7.1.2	Other Nanostructures and Microstructures	129
	7.2	Physic	cal Storage Using Metal-Organic Frameworks	130
	7.3	Clathrate Hydrates		132
	7.4	Summary		135
		Refere	ences	135
8	Hyd	rogen	Utilization: Combustion	139
	8.1	Basics	s about Combustion	139
	8.2	Mecha	anism of Combustion	140
	8.3	Major	Factors Affecting Combustion	143
	8.4	Cataly	vtic Combustion	146
	8.5	Summ	nary	149
		Refere	ences	150
9	Hyd	rogen	Utilization: Fuel Cells	153
	9.1	Basics	s of Fuel Cells	153
		9.1.1	The Rational Development of Fuel Cells	153
		9.1.2	Work Principles of Fuel Cells	154
		9.1.3	Operation of Fuel Cells	155

viii Contents

	9.2	Types of Fuel Cells	157		
		9.2.1 Alkaline Fuel Cell (AFC)	157		
		9.2.2 Proton Exchange Membrane Fuel Cell (PEMFC)	157		
		9.2.3 Phosphoric Acid Fuel Cell (PAFC)	160		
		9.2.4 Molten Carbonate Fuel Cell (MCFC)	162		
		9.2.5 Solid Oxide Fuel Cell (SOFC)	163		
	9.3	Catalysts for Oxygen Reduction Reaction of Fuel Cells	163		
		9.3.1 Pt-Based Catalysts	164		
		9.3.2 Nonnoble Metal Catalysts	164		
	9.4	Fuel Processing	168		
	9.5	Applications of Fuel Cells	169		
	9.6	Summary	171		
		References	172		
10	Hydr	Hydrogen Utilization in Chemical Processes			
	10.1	Background	177		
	10.2	Hydrogen Utilization in Petroleum Industry	177		
		10.2.1 Hydrocracking	177		
		10.2.2 Hydroprocessing	180		
	10.3	Hydrogen Utilization in Chemical Industry	181		
		10.3.1 Ammonia Production: The Haber Process	181		
		10.3.2 Hydrogenation of Unsaturated Hydrocarbons	182		
	10.4	Hydrogen Utilization in Metallurgical Industry	182		
		10.4.1 Ore Reduction	182		
	10.5	Hydrogen Utilization in Manufacturing Processes	184		
		10.5.1 Welding Gas: Oxy-Hydrogen Welding	184		
		10.5.2 Coolant	185		
	10.6	Hydrogen Utilization in Physics			
		10.6.1 Lifting Gas	187		
		10.6.2 Superconductor Industry	187		
		10.6.3 Semiconductor Industry	187		
	10.7	Summary	188		
		References	188		
In	dex		191		