

Contents

Preface to the Second Edition *xvii*

Preface to the First Edition *xix*

1	Introduction	1
	<i>Klaus Reders and Andrea Schütze</i>	
1.1	History of the Spark Ignited “Otto” Engine and of Gasoline	3
1.2	History of the Diesel Engine and of Diesel Fuel	14
1.3	History of Alternative Fuels	19
1.3.1	Ethanol	19
1.3.2	Methanol	24
1.3.3	Vegetable Oils and Hydrotreated Vegetable Oils (HVOs)	24
1.3.4	Biodiesel/FAME	25
1.3.5	Liquefied Petroleum Gas (LPG)	28
1.3.6	Natural Gas	30
1.4	Emission Regulations Worldwide	33
1.4.1	Europe	35
1.4.2	United States	41
1.4.3	Japan	48
1.4.4	China	51
1.5	Well-to-Wheel Analysis of Alternative Fuels	53
1.5.1	Life-cycle Assessment	54
1.5.2	Well-to-Wheel	55
1.5.3	Boundary Conditions of the JRC Study	56
1.5.4	Summary of Results of the JRC Study	57
1.5.4.1	Alternative Liquid Fuels	60
1.5.4.2	Alternative Gaseous Fuels	61
1.5.4.3	Electricity and Hydrogen	61
1.5.4.4	2020+ Horizon	62
	References	64

Part I Automotive Fuels 69**2 Engine Technology 71***Werner Dabelstein, Arno Reglitzky, Andrea Schütze, and Klaus Reders*

2.1 Otto Engines 71

2.2 Diesel Engines 73

References 75

3 Fuel Composition and Engine Efficiency 77*Werner Dabelstein, Arno Reglitzky, Andrea Schütze, Klaus Reders, and Andreas Brunner*

3.1 Fuel Composition and Engine Efficiency 77

3.1.1 Quality Aspects of Gasoline 77

3.1.1.1 Octane Quality 77

3.1.1.2 Volatility 79

3.1.1.3 Fuel Composition to Reduce Toxicity and Exhaust Emissions 80

3.1.1.4 Stability, Cleanliness, etc. 83

3.1.1.5 Performance Additives 84

3.1.2 Quality Aspects of Diesel Fuels 84

3.1.2.1 Ignition Quality 84

3.1.2.2 Density 85

3.1.2.3 Sulfur Content 85

3.1.2.4 Cold Flow Properties 85

3.1.2.5 Lubricity 85

3.1.2.6 Viscosity 86

3.1.2.7 Volatility 86

3.1.2.8 Diesel Fuel Stability, Cleanliness, and Safety 86

3.1.2.9 Diesel Fuel Effects on Exhaust Emissions 86

3.1.2.10 Performance Additives 88

References 88

4 Fuel Components: Petroleum-derived Fuels 91*Werner Dabelstein, Arno Reglitzky, Andrea Schütze, and Klaus Reders*

4.1 Petroleum-derived Fuels 91

4.1.1 Gasoline Components 91

4.1.1.1 Straight-run Gasoline 91

4.1.1.2 Thermally Cracked Gasoline 93

4.1.1.3 Catalytically Cracked Gasoline 93

4.1.1.4 Catalytic Reformate (Platformate) 94

4.1.1.5 Isomerase 94

4.1.1.6 Alkylate 94

4.1.1.7 Polymer Gasoline 94

4.1.1.8 Oxygenates 95

4.1.2 Diesel Fuel Components 95

4.1.2.1 Straight-run Middle Distillate 95

4.1.2.2 Thermally Cracked Gas Oil 96

4.1.2.3 Catalytically Cracked Gas Oil 96

4.1.2.4	Hydrocracked Gas Oil	97
4.1.2.5	Kerosene	97
4.1.2.6	Biofuel Components	97
4.1.2.7	Synthetic Diesel Fuel	98
4.1.3	Storage and Transportation	98
	References	99
5	Liquefied Petroleum Gas	101
	<i>Stephen M. Thompson, Gary Robertson, Robert Myers, and Andrea Schütze</i>	
5.1	Introduction	101
5.2	Properties	102
5.3	Production and Processing	103
5.3.1	Recovery from Natural Gas	103
5.3.1.1	Recovery and Manufacture in the Refinery	103
5.4	Purification	108
5.4.1	Adsorptive Purification	109
5.4.2	Absorptive Purification	109
5.5	Storage and Transportation	110
5.5.1	Aboveground Storage	110
5.5.2	Underground Storage	110
5.5.3	Transportation	111
5.6	Uses	111
5.6.1	LPG Standards and Regulations	112
5.6.1.1	Refueling Infrastructure	112
5.6.1.2	Vehicle Conversions to LPG	113
5.6.2	Environmental Benefits	113
5.6.2.1	Outlook	115
5.7	Safety Aspects	115
5.7.1	Occupational Health	116
	References	116
6	Natural Gas	119
	<i>Klaus Reders, Margret Schmidt, and Andrea Schütze</i>	
6.1	Occurrence	119
6.2	Composition	121
6.3	Processing	123
6.3.1	Oil and Condensate Removal	124
6.3.2	Water Removal	124
6.3.3	Separation of Natural Gas Liquids	125
6.3.3.1	Cryogenic Expansion Process	126
6.3.4	Sulfur and Carbon Dioxide Removal	126
6.4	Transport/Distribution/Local Blending	126
6.5	Properties and Specifications	127
6.6	Natural Gas as Automotive Fuel	129
6.6.1	Vehicle Refueling Systems	133
6.6.1.1	Slow-Fill Refueling	133
6.6.1.2	Fast-Fill Refueling	134

6.6.2	Vehicle and Engine Concepts	134
6.6.2.1	Vehicle Technology	135
6.6.3	CNG Vehicles in the Market	137
6.6.4	Vehicle Fuel Supply System	137
6.6.5	Combustion and Emissions	139
6.7	Safety Aspects	141
6.8	Biomethane	141
6.8.1	Production	142
6.8.1.1	Anaerobic Fermentation	145
6.8.1.2	Biogas from Solids	146
6.8.2	Upgrading of Biogas to Natural Gas Quality	147
6.8.2.1	Water Scrubbing and Physical Scrubbing	147
6.8.2.2	Chemical Absorption	148
6.8.2.3	Membrane Separation	148
6.8.2.4	Pressure Swing Adsorption (PSA)	149
6.8.2.5	Cryogenic Separation	149
6.8.3	Storage and Transportation	149
6.8.3.1	Storage	149
6.8.3.2	Distribution	150
6.8.4	Biomethane Regulations	150
6.8.4.1	Regulations and Standards	151
6.8.5	Well-to-wheel Analysis for LPG, CNG, and Biomethane	152
6.8.5.1	Well-to-Tank Analysis	152
6.8.5.2	Compressed Biomethane (CBM)	155
6.8.5.3	Well-to-Wheels Analysis	156
	References	158
7	Synthetic Diesel Fuels	161
	<i>H.P. Calis, Wolfgang Lüke, Ingo Drescher, and Andrea Schütze</i>	
7.1	XTL Fuels	162
7.1.1	History	162
7.1.2	XTL Production Process	162
7.1.2.1	Fischer–Tropsch Process	162
7.1.2.2	IH ² Technology	166
7.1.2.3	BTL Fuels	168
7.1.3	GTL and BTL Fuel Characteristics	170
7.1.3.1	Cold Flow Performance	171
7.1.3.2	Lubricity Performance	174
7.1.3.3	Impact on Injector Cleanliness and Spray Characteristics	174
7.1.3.4	Advantages of Synthetic Fuels for Emission Control	175
7.1.4	Outlook	178
7.2	DME (Dimethyl Ether) and OME Fuels	180
7.2.1	Introduction	180
7.2.2	Fuel Standards	181
7.2.3	Fuel Properties	183
7.2.4	Infrastructure and Safety	186
7.2.4.1	Use as Fuel	187

7.3	Well-to-Wheel (WTW) Analysis for XTL and DME Fuels	190
7.3.1	Well-to-Wheels Analysis for XTL	190
7.3.2	Well-to-Tank Analysis for DME	193
7.4	Well-to-Wheel Analysis for XTL and DME	195
	References	196
8	Synthetic Gasoline Fuels	201
	<i>Andrea Schütze</i>	
8.1	GTL Naphtha	201
8.2	Methanol to Gasoline Process (MTG)	202
8.3	Production Process	202
8.4	Fuel Properties	203
	References	204
9	Ethanol	207
	<i>Andrea Schütze</i>	
9.1	Production	210
9.1.1	Milling	211
9.1.2	Processing of Starch/Maize Mash	212
9.1.3	Fermentation of Glucose	213
9.1.4	Distillation and Increase of Ethanol Concentration	213
9.2	Feedstock	214
9.3	Land Use	215
9.3.1	Direct Land Use Change Emissions (DLUC)	217
9.3.2	Indirect Land Use Change (ILUC)	217
9.4	Nitrogen Oxide Emissions	217
9.5	Water Foot Print and Impact on Water Table	219
9.6	Other Environmental Effects	219
9.6.1	Soil Quality/Erosion	219
9.6.2	Eutrophication and Acidification	219
9.6.3	Biodiversity	219
9.7	Bioethanol Made from Lignocellulose	220
9.8	Fuel Standards	221
9.9	Fuel Properties	224
9.9.1	Octane Number	224
9.9.1.1	Volatility and Distillation	226
9.9.1.2	Heat of Vaporization	228
9.9.1.3	Energy Content	228
9.9.1.4	Water Content	228
9.9.1.5	Corrosion Protection	228
9.9.1.6	Denaturant and Denaturant Content	229
9.9.1.7	Material Compatibility	229
9.9.1.8	Lubricity	229
9.9.1.9	Emissions	229
9.10	Well-to-Wheels Analysis for Fuel Ethanol and Ethanol Gasoline Blends	230
9.10.1	Pathways	230

9.10.1.1	Sugar Beet to Ethanol	230
9.10.1.2	Wheat to Ethanol	231
9.10.1.3	Straw to Ethanol	231
9.11	WTT Analysis for Bioethanol	236
9.12	WTW Analysis	237
	References	240
10	Methanol	245
	<i>Martin Bertau, Michael Kraft, Ludolf Plass, and Hans-Jürgen Wernicke</i>	
10.1	Introduction	248
10.2	Physical and Chemical Properties	249
10.3	Production of Methanol	249
10.3.1	Methanol Production Capacities and Markets	250
10.3.2	Conventional Methanol Production Processes	252
10.3.2.1	Synthesis Gas Generation	252
10.3.2.2	Methanol Synthesis	255
10.3.2.3	Liquid Phase Methanol Synthesis (LPMEOH®)	258
10.3.2.4	Methanol Distillation	258
10.3.3	Renewable Methanol Production Processes	259
10.3.3.1	CO ₂ – Hydrogenation	260
10.4	Methanol as Fuel	261
10.4.1	History	263
10.4.2	Uses	264
10.4.2.1	Methanol as a Fuel for Otto Engines	264
10.4.2.2	Vehicle Developments	265
10.4.2.3	Conclusions	268
10.4.2.4	Methanol as Marine Fuel	269
10.4.3	Safety Aspects	270
10.4.3.1	Explosion and Fire Control	270
10.4.3.2	Fire Prevention	271
10.4.3.3	Fire Fighting	271
10.4.3.4	Small-scale Storage	271
10.4.3.5	Large-scale Storage	271
10.4.3.6	Large-scale Transportation	272
10.4.3.7	Safety Regulations Governing Transportation	272
10.4.3.8	Methanol as a Hazard	272
10.5	Methanol-based Derivatives as Fuels and Fuel Additives	273
10.5.1	Methanol-to-Gasoline (MTG)	274
10.5.2	Methyl <i>tert</i> -Butyl Ether (MTBE)	276
10.5.3	<i>tert</i> -Amyl Methyl Ether (TAME)	278
10.5.4	Dimethyl Ether (DME)	279
10.5.5	Oxymethylene Ether (OME)	281
10.5.6	Dimethyl Carbonate (DMC) and Methyl Formate (MF)	285
10.6	Economic Aspects	289
10.6.1	Gas-based Methanol	289
10.6.2	Coal-based Methanol	289
10.6.3	Biomass-based Methanol	291

10.6.4	Renewable Methanol Based on the Recycle of Carbon Dioxide	292
10.7	Outlook	297
	References	297
11	2,5-Dimethylfuran (DMF) and 2-Methylfuran (MF)	307
	<i>Andrea Schütze</i>	
11.1	Synthesis of Dimethylfuran	307
11.2	Properties of 2,5-Dimethylfuran and Methylfuran	309
11.3	Combustion and Emissions	311
	References	312
12	Alternative Biofuel Options – Diesel	315
	<i>Andrea Schütze</i>	
12.1	Biomass-to-Liquids (BTL)	315
12.2	Biodiesel (FAME)	316
12.2.1	Production	318
12.2.1.1	Introduction	318
12.2.1.2	Industrial Process	321
12.2.1.3	Feedstock	322
12.2.1.4	Microalgae	324
12.2.2	Analytical Methods	326
12.2.2.1	Ester Content and Fatty Acid Composition	326
12.2.2.2	Polyunsaturated Methyl Esters Content	327
12.2.2.3	Glycerol and Glyceride Content	328
12.2.3	Fuel Standards	332
12.2.3.1	United States	332
12.2.3.2	Europe	336
12.2.4	Fuel Properties	337
12.2.4.1	Cetane Number	338
12.2.4.2	Density and Energy Content	339
12.2.4.3	Kinematic Viscosity	339
12.2.4.4	Cold Temperature Properties	339
12.2.4.5	Filterability	341
12.2.4.6	Distillation	341
12.2.4.7	Fuel Stability	341
12.2.4.8	Water Content and Sediment	343
12.2.4.9	Lubricity	343
12.2.4.10	Material Compatibility	343
12.2.4.11	Engine Deposits	344
12.2.4.12	Emissions	345
12.3	Vegetable Oils (VO)	345
12.3.1	Production	346
12.3.2	Fuel Properties	346
12.3.2.1	Kinematic Viscosity	347
12.3.2.2	Cetane Number	348
12.3.2.3	Flash Point	348
12.3.2.4	Carbon Residue	348

12.3.2.5	Heating Value	348
12.3.2.6	Density	348
12.3.2.7	Iodine Number	349
12.3.2.8	Fuel Stability	349
12.3.2.9	Calcium, Magnesium, and Phosphorus	350
12.3.2.10	Total Contamination and Water Content	350
12.3.2.11	Acid Value	350
12.3.3	Fuel Standards	350
12.4	Hydrotreated Vegetable Oils	351
12.4.1	Production	352
12.4.1.1	Process	352
12.4.1.2	Production Plants	354
12.4.2	Fuel Standard and Properties	354
12.4.2.1	Density and Energy Content	355
12.4.2.2	Distillation Characteristics	355
12.4.2.3	Cold Temperature Properties	356
12.4.2.4	Cetane Number	356
12.4.2.5	Fuel Stability	356
12.4.2.6	Lubricity	357
12.4.2.7	Material Compatibility	357
12.4.2.8	Emissions and Combustion	357
12.5	Well-to-Wheel Analysis of FAME and HVO Fuels	357
12.5.1	FAME Fuels	359
12.5.1.1	WTT Analysis	359
12.5.1.2	WTW Analysis	361
12.5.2	HVO Fuels	363
12.5.2.1	WTT Analysis	363
12.5.2.2	WTW Analysis	364
	References	366
13	Hydrogen	373
	<i>Lalit M. Das</i>	
13.1	Introduction	373
13.2	Life Cycle Analysis	373
13.3	Hydrogen Production	374
13.4	Historical Overview of Hydrogen Engine: Research and Development	375
13.5	Properties of Hydrogen which Influence Engine Combustion	377
13.6	Undesirable Combustion Phenomena	381
13.7	Design Criteria for Hydrogen Engines	382
13.8	Hydrogen-fueled Wankel Engine	384
13.9	Performance Characteristic of a Hydrogen-fueled SI Engine	385
13.10	Exhaust Emissions	386
13.11	Combustion Characteristics	387
13.12	Hydrogen Use in CI Engines	389
13.13	Hydrogen-CNG Blend	391
13.14	Safety Criteria for Hydrogen Engines	392

13.15	Hydrogen Detection	393
13.16	Storage of Hydrogen	393
13.17	Hydrogen Transportation and Distribution	394
13.18	Hydrogen Vehicles based on Internal Combustion Engine	395
13.19	Conclusion	398
	References	398
14	Octane Enhancers	403
	<i>Marco Di Girolamo, Maura Brianti, and Mario Marchionna</i>	
14.1	Introduction	403
14.2	Technical Information	405
14.2.1	Combustion in Otto Engines	405
14.2.2	Knock Phenomena	406
14.2.3	Octane Number	406
14.3	Types of Octane Enhancers	409
14.4	Metal-containing Additives	409
14.4.1	Alkyl Lead Compounds	412
14.4.2	Methylcyclopentadienyl Manganese Tricarbonyl	414
14.5	Ashless Octane Enhancers	415
14.5.1	Heteroatom-based Components	415
14.5.1.1	History of Fuel Oxygenates	417
14.5.1.2	Properties of Oxygenates	420
14.5.1.3	Production	424
14.5.1.4	Toxicology	426
14.5.2	Pure Hydrocarbon Components	427
	References	428
	Further Reading	430
15	Hybrid and Electrified Powertrains	431
	<i>Jakob Andert, Maximilian Wick, Rene Savelsberg, and Michael Stapelbroek</i>	
15.1	Introduction	431
15.2	Classification	432
15.2.1	Topologies	432
15.2.1.1	Serial Hybrids	433
15.2.1.2	Parallel Hybrids	434
15.2.1.3	Power-split Hybrids	435
15.2.2	Degree of Hybridization	436
15.3	Functionalities	437
15.3.1	Regenerative Braking	437
15.3.2	Load Point Shift/Boosting	438
15.3.3	E-drive and Sailing	439
15.4	Battery	440
15.4.1	NiMH Batteries	441
15.4.2	Li-ion Batteries	442
15.5	Energy Management	443
15.6	Market Situation and Outlook	444
	References	444

16	Fuel Cells	447
	<i>Sören Tinz, Steffen Dirkes, Marius Walters, and Jakob Andert</i>	
16.1	Transportation Applications	447
16.2	Fundamentals	449
16.2.1	Auxiliaries	452
16.2.1.1	Air Supply System	452
16.2.1.2	Hydrogen Supply System	454
16.2.1.3	Cooling Circuit	454
16.2.1.4	HV Architecture	455
16.2.1.5	Controls	455
16.2.1.6	Integrated System Design	455
16.2.2	Onboard Hydrogen Storage	456
16.3	Costs, Durability, and Reliability	457
16.4	Cold and Freeze Start	459
16.5	Efficiency	459
16.6	Summary	460
	References	460

Part II Automobile Exhaust Control 465

17	Introduction	467
	<i>Martin Votsmeier, Thomas Kreuzer, Jürgen Gieshoff, Gerhard Lepperhoff, and Barbara Elvers</i>	
	Reference	469
18	Pollutant Formation and Limitation	471
	<i>Martin Votsmeier, Thomas Kreuzer, Jürgen Gieshoff, Gerhard Lepperhoff, and Barbara Elvers</i>	
18.1	Carbon Monoxide	471
18.2	Hydrocarbons	471
18.3	Oxides of Nitrogen (NO _x)	472
18.4	Particulate Emissions	472
18.5	Carbon Dioxide (CO ₂)	473
18.6	Sulfur Compounds	473
	Reference	474
19	Catalytic Exhaust Aftertreatment, General Concepts	475
	<i>Martin Votsmeier, Thomas Kreuzer, Jürgen Gieshoff, Gerhard Lepperhoff, and Barbara Elvers</i>	
19.1	The Physical Design of the Catalytic Converter	475
19.1.1	Ceramic Monoliths	477
19.1.2	Metallic Monoliths	477
19.1.3	Particulate Filters	478
19.1.4	Extruded Catalysts	478
19.2	The Washcoat	478
19.3	The Catalytic Material	480
19.4	Production of Catalysts	480
	References	481

20	Catalytic Aftertreatment of Stoichiometric Exhaust Gas 483
	<i>Martin Votsmeier, Thomas Kreuzer, Jürgen Gieshoff, Gerhard Lepperhoff, and Barbara Elvers</i>
20.1	Three-way Catalysts 484
20.2	Oxygen Storage in Three-way Catalysts 485
20.3	Precious Metals in Three-way Catalysis 487
	References 487
21	Exhaust Aftertreatment for Diesel Vehicles 489
	<i>Martin Votsmeier, Thomas Kreuzer, Jürgen Gieshoff, Gerhard Lepperhoff, and Barbara Elvers</i>
21.1	The Diesel Oxidation Catalyst 489
21.1.1	Oxidation of Particulate Emissions 490
21.1.2	Oxidation of SO ₂ 490
21.1.3	Oxidation of NO 490
21.1.4	Particulate Filter Regeneration 490
21.1.5	Pt/Pd Dispersion 491
21.2	The Particulate Filter 491
21.2.1	Soot Oxidation by Oxygen 492
21.2.2	Soot Oxidation by NO ₂ 492
21.2.3	Ash Load 493
21.2.4	Open Filter Systems 493
21.3	NO _x Treatment of Oxygen-rich Exhaust 494
21.3.1	HC–DeNO _x 494
21.3.2	The NO _x Adsorber Catalyst 495
21.3.3	Selective Catalytic Reduction (SCR) with Ammonia 496
21.3.4	NH ₃ Generation Onboard 496
21.3.5	Vanadium SCR Catalysts 497
21.3.6	Zeolite-based SCR Catalysts 498
21.3.7	Oxidation Catalyst Upstream of the SCR Catalyst 498
22	Exhaust Aftertreatment for Lean-burn Gasoline Engines 499
	<i>Martin Votsmeier, Thomas Kreuzer, Jürgen Gieshoff, Gerhard Lepperhoff, and Barbara Elvers</i>
23	Conclusion and Outlook 501
	<i>Martin Votsmeier, Thomas Kreuzer, Jürgen Gieshoff, Gerhard Lepperhoff, and Barbara Elvers</i>
	Part III Aviation Fuels 503
24	Aviation Turbine Fuels 505
	<i>Geoff J. Bishop and Barbara Elvers</i>
24.1	History 505
24.1.1	Fuel Types and Specifications 505
24.1.1.1	Specification Requirements 507

24.1.1.2	Fuel Properties	507
24.1.1.3	Nonspecification Properties	516
24.1.2	Production	518
24.1.2.1	Fuel	518
24.1.2.2	Additives	520
24.1.3	Handling, Storage, and Transportation	522
24.1.3.1	System Descriptions	522
24.1.3.2	Contamination-removal Equipment	522
24.1.4	Legal Aspects	523
24.1.5	Environmental Aspects	523
24.1.6	Economic Aspects	523
24.1.7	Future Trends	524
24.1.7.1	Petroleum-Derived Fuels	524
24.1.7.2	Alternative Fuels	524
	References	525
	Further Reading	527

25 Aviation Gasoline (Avgas) 529

Geoff J. Bishop and Barbara Elvers

25.1	History	530
25.2	Avgas Grades	530
25.2.1	Avgas 100	530
25.2.2	Avgas 100LL	530
25.2.3	Avgas 100VLL	531
25.2.4	Avgas UL82	531
25.2.5	Avgas UL87	531
25.2.6	Avgas UL91	531
	Reference	531
	Further Reading	531

Part IV Marine Fuels 533

26 Marine Fuels 535

Christopher Friedrich Wirz, Torsten Mundt, and Klaus Reders

26.1	History	535
26.2	Specifications	536
26.3	Composition	536
26.4	Properties	537
26.4.1	Distillate Fuels	537
26.4.2	Residual Fuels	537
	Reference	540

Index 541