



# Diesel Emissions and Their Control

**W. Addy Majewski and Magdi K. Khair**

# Table of Contents

Preface.....	v
<b>Part I Diesel Engine Basics .....</b>	<b>1</b>
<i>Chapter 1 The Case for the Diesel Engine .....</i>	<i>3</i>
1.1 Introduction.....	3
1.2 What Is a Diesel Engine?.....	3
1.3 Types of Diesel Internal Combustion Engines.....	4
1.4 Energy Conservation and the Diesel Engine.....	5
1.5 What Are the Advantages of Diesel Engines? .....	13
1.5.1 Emissions.....	13
1.5.2 Compression Ratio .....	14
1.5.3 Friction Losses.....	15
1.5.4 Diesel Fuel Safety.....	15
1.5.5 Durability.....	15
1.5.6 Reliability .....	15
1.5.7 Ease of Breathing and Lower Pumping Losses .....	15
References.....	16
<i>Chapter 2 Engine Fundamental and Design Parameters .....</i>	<i>17</i>
2.1 Introduction.....	17
2.2 Heat Engines .....	17
2.3 Operation of Reciprocating Internal Combustion Diesel Engines .....	18
2.3.1 Operation of Two-Stroke Engines .....	18
2.3.2 Scavenging in Two-Stroke Engines .....	19
2.3.3 Definition of Basic Performance Parameters for Two-Stroke Engines .....	20
2.3.4 Scavenging Characteristics in Various Two-Stroke Designs .....	22
2.3.5 Operation of Four-Stroke Engines.....	22
2.4 Assessment of Engine Performance.....	26
2.5 The First and Second Laws of Thermodynamics.....	27
2.6 Mass Conservation in Combustion Thermodynamics .....	28
2.7 Stoichiometric Ratio in Diesel Combustion.....	29
2.8 Additional Performance Parameters and Their Definition.....	29
2.8.1 Power Output.....	29
2.8.2 Indicated Power .....	30
2.8.3 Mechanical Efficiency .....	31
2.8.4 Indicated Mean Effective Pressure .....	31
2.8.5 Brake Mean Effective Pressure.....	31
2.8.6 Specific Fuel Consumption.....	32
2.8.7 Volumetric Efficiency .....	32
2.8.8 Engine Specific Weight and Volume.....	32
2.9 Performance Curves.....	32
References.....	33
<i>Chapter 3 Air Induction for Diesel Engines .....</i>	<i>35</i>
3.1 Introduction.....	35
3.2 Methods of Charge Air Boosting .....	35
3.3 Types of Superchargers .....	35
3.3.1 The Roots Blower.....	36

3.3.2	The Sliding Vane Compressor .....	37
3.3.3	The Screw Compressor.....	37
3.3.4	The Rotary Piston Supercharger.....	38
3.3.5	The Spiral-Type Supercharger.....	38
3.3.6	The Variable-Displacement Piston Supercharger .....	38
3.3.7	The Centrifugal Compressor Supercharger .....	38
3.4	Turbochargers .....	41
3.5	Types of Turbochargers .....	44
3.5.1	Waste-Gated Turbochargers.....	44
3.5.2	Variable-Geometry Turbochargers .....	44
3.6	Supercharger-Aided Turbochargers .....	45
3.7	Compressor or Turbine A/R Ratio .....	46
3.8	Practical Embodiments .....	47
3.9	Sequential Turbocharging .....	48
3.10	Turbocompounding .....	48
3.11	Wave Supercharging .....	48
	References.....	50
<i>Chapter 4</i>	Diesel Fuel Injection .....	51
4.1	Introduction.....	51
4.2	Purposes of the Fuel Injection System.....	51
4.3	Types of Diesel Fuel Injection Systems.....	52
4.4	The Pump-Line-Nozzle System.....	52
4.4.1	The P-L-N In-Line Pump System.....	55
4.4.2	The P-L-N Distributor/Rotary Pump System .....	66
4.4.3	The P-L-N Unit Pump System .....	68
4.5	The Unit Injector System .....	69
4.6	The Common-Rail Injection System .....	70
4.7	More on P-L-N Systems .....	71
4.8	Modernizing the Diesel Fuel Injection System.....	72
4.9	Modernizing the Pump-Line-Nozzle System.....	72
4.9.1	Electronic Control of the In-Line Pump System .....	72
4.9.2	Electronic Control of the Distributor Pump System .....	76
4.9.3	Electronic Control of the Unit Pump System .....	77
4.10	Modernizing the Unit Injector System.....	78
4.11	Electronically Controlled Common-Rail System .....	79
4.12	Components of an Electronically Controlled Injection System.....	80
4.12.1	Sensors.....	82
4.12.2	Electronic Control Unit .....	82
4.12.3	Actuators.....	83
4.13	Innovative Injection Systems .....	84
4.13.1	The Bendix Diesel Engine Control Unit Injector System .....	84
4.13.2	The Hydraulically Actuated, Electronically Controlled Unit Injector.....	85
4.13.3	Cummins Accumulator Pump System.....	90
4.14	Conclusion .....	91
	References.....	91
<i>Chapter 5</i>	Combustion in Diesel Engines.....	93
5.1	Introduction.....	93
5.2	Components of the Combustion Process .....	93
5.3	Fuel and Air Distribution in the Fuel Spray of a DI Diesel .....	94
5.3.1	Lean Flame Region.....	95
5.3.2	Lean Flame-Out Region .....	95
5.3.3	Spray Core .....	95
5.3.4	Spray Tail.....	96
5.3.5	After-Injection or Secondary Injection .....	96

5.3.6	Fuel Deposited on the Walls .....	96
5.4	Heat Release Rates in DI Engines .....	97
5.5	Additional Details of Spray Formation.....	97
5.5.1	Spray Formation during Injection.....	98
5.5.2	Spray Atomization .....	98
5.5.3	Spray Penetration.....	99
5.5.4	Droplet Size Distribution.....	99
5.6	The Three Phases of Diesel Combustion .....	100
5.6.1	Ignition Delay .....	100
5.6.2	Premixed Combustion .....	102
5.6.3	Rate-Controlled Combustion.....	102
	References.....	103
<i>Chapter 6</i>	Emissions Formation in Diesel Engines .....	105
6.1	Emission Formation in Diesel Engines.....	105
6.2	Formation of Hydrocarbons in Diesel Engines.....	105
6.2.1	Air-to-Fuel Ratio .....	106
6.2.2	Effect of Engine Load.....	107
6.2.3	Effect of After-Injection and Secondary Injection.....	107
6.2.4	Effects of Cold Starts and Misfires.....	107
6.2.5	Effect of Turbocharging.....	108
6.2.6	Effect of Nozzle Opening Pressure .....	108
6.2.7	Effect of Injection Timing .....	108
6.2.8	Effect of Intake Swirl.....	108
6.2.9	Final Comments on Sensitivity of HC to the Fuel System.....	109
6.3	Formation of Carbon Monoxide in Diesel Engines .....	109
6.4	Formation of Nitrogen Oxides in Diesel Engines.....	110
6.4.1	Fuel-Air Ratio.....	111
6.4.2	Effect of Nozzle Opening Pressure .....	111
6.4.3	Effect of Injection Timing .....	111
6.4.4	Effect of Cetane Number.....	112
6.4.5	Effect of Swirl .....	112
6.4.6	Effect of Intake Charge Dilution .....	112
6.5	Formation of Particulate Matter in Diesel Engines.....	112
6.5.1	Constituents and Sources of Particulate Matter.....	112
6.5.2	Carbonaceous Particulate Release and Oxidation .....	112
6.5.3	Summary of Potential Sources of Particulate Matter .....	113
6.6	Smoke in Diesel Engines .....	114
	References.....	116
<b>Part II</b>	<b>Diesel Emissions.....</b>	119
<i>Chapter 7</i>	Characterization of Emissions .....	121
7.1	What Are Diesel Emissions?.....	121
7.1.1	Diesel Combustion Products .....	121
7.1.2	Diesel Emission Levels.....	122
7.2	Gaseous Emissions.....	123
7.2.1	Nitrogen Oxides.....	123
7.2.2	Hydrocarbons .....	123
7.2.3	Carbon Monoxide .....	124
7.2.4	Sulfur Dioxide .....	124
7.2.5	Nitrous Oxide .....	125
7.2.6	Hydrogen .....	126
7.3	Diesel Particulate Matter.....	126
7.3.1	What Are Diesel Particulates?.....	126

7.3.2	Composition of Diesel Particulates .....	127
7.3.3	Solid Fraction .....	128
7.3.4	Soluble Organic Fraction.....	130
7.3.5	Sulfate Particulates .....	133
7.3.6	Particle Size Distribution.....	133
7.4	Diesel Exhaust Particle Size .....	134
7.4.1	Diesel Particle Size Distribution.....	134
7.4.2	Particle Distributions from New Diesel Engines.....	135
7.4.3	Spark-Ignited Engines .....	137
7.4.4	Influence of Particulate Sampling.....	139
7.4.5	Nanoparticles: Composition and Formation.....	140
7.4.6	Engine Nanoparticle Issues .....	143
	References.....	143
<i>Chapter 8</i>	Health and Environmental Effects .....	147
8.1	Overview .....	147
8.1.1	Toxic Compounds in Diesel Exhaust.....	147
8.1.2	Inventories and Exposures .....	148
8.1.3	Effects on Health and Environment.....	149
8.1.4	Summary.....	150
8.2	Diesel Emission Inventory .....	150
8.2.1	Diesel Engines and Air Pollution .....	150
8.2.2	United States.....	151
8.2.3	European Union.....	154
8.3	Exposure to Diesel Exhaust .....	155
8.3.1	Introduction .....	155
8.3.2	Exposure Estimation.....	156
8.3.3	Diesel Particulate Matter .....	156
8.3.4	Polynuclear Aromatic Hydrocarbons .....	158
8.3.5	Hydrocarbons and Aldehydes.....	159
8.4	Health Effects of Gas Phase Components.....	159
8.4.1	Introduction .....	159
8.4.2	Carbon Monoxide .....	160
8.4.3	Sulfur Dioxide .....	161
8.4.4	Nitric Oxide .....	162
8.4.5	Nitrogen Dioxide .....	162
8.5	Health Effects of Diesel Particulates .....	163
8.5.1	Introduction .....	163
8.5.2	Noncancer Health Effects .....	164
8.5.3	Carcinogenicity of Diesel Exhaust .....	165
8.5.4	Future Issues .....	167
8.6	Environmental Effects of Emissions .....	167
8.6.1	Pollutants and Air Quality .....	167
8.6.2	Photochemical Smog .....	169
8.6.3	Acid Rain .....	170
8.6.4	Global Warming .....	170
8.6.5	Reduced Atmospheric Visibility .....	172
	References.....	172
<i>Chapter 9</i>	Measurement of Emissions .....	175
9.1	Overview .....	175
9.1.1	Introduction .....	175
9.1.2	Emission Test Cycles .....	176
9.1.3	Sampling and Analysis .....	177
9.2	Gas-Phase Measurements .....	179
9.2.1	Techniques of Gas Analysis.....	179

9.2.2	Analysis of Exhaust Pollutants .....	181
9.3	Particulate Matter Measurements.....	182
9.3.1	Introduction .....	182
9.3.2	Gravimetric Method .....	183
9.3.3	Particle Number and Size Analysis .....	184
9.3.4	Instrumental Analysis of Other PM Parameters .....	190
9.3.5	Smoke and Smoke Opacity.....	192
9.4	Measurement of Ambient Diesel Aerosol .....	194
9.4.1	Aerosol Sampling and Analysis.....	194
9.4.2	Measurement in Ambient Air .....	196
9.4.3	Measurement in Occupational Health Settings .....	197
9.4.4	Measurement in Mines .....	199
9.4.5	Gas-Phase Measurements .....	201
	References.....	202
<i>Chapter 10</i>	Emission Regulations .....	207
10.1	Historical Background .....	207
10.2	Types of Emission Regulations.....	209
10.3	Emission Test Cycles .....	210
10.3.1	U.S. Heavy-Duty FTP Transient Cycle .....	211
10.3.2	U.S. FTP-75 Cycle .....	211
10.3.3	European Stationary Cycle .....	211
10.3.4	European Transient Cycle.....	213
10.3.5	ECE 15 + EUDC .....	213
10.3.6	ISO 8178.....	214
10.4	Selected Diesel Emission Standards .....	214
10.4.1	Overview.....	214
10.4.2	United States.....	214
10.4.3	European Union.....	218
10.5	Selected Diesel-Related Occupational Health Regulations .....	220
10.5.1	United States.....	220
10.5.2	Germany .....	222
	References.....	222
<b>Part III</b>	<b>Diesel Fuels.....</b>	<b>225</b>
<i>Chapter 11</i>	Petroleum Diesel Fuel.....	227
11.1	What Is Diesel Fuel?.....	227
11.1.1	Components of Diesel Fuel .....	227
11.1.2	Diesel Fuel Properties.....	227
11.1.3	Typical Specifications .....	231
11.2	Fuel Properties and Emissions .....	233
11.2.1	Introduction .....	233
11.2.2	Heavy-Duty Engines.....	234
11.2.3	Light-Duty Engines .....	237
	References.....	237
<i>Chapter 12</i>	Alternative Diesel Fuels.....	239
12.1	Overview of Alternative Diesel Fuels .....	239
12.1.1	Environmental Driving Forces.....	239
12.1.2	Alternative Fuel Options.....	240
12.1.3	Resource Use and Energy Efficiency .....	240
12.2	Synthetic Diesel Fuel .....	241
12.2.1	Introduction .....	241
12.2.2	Fisher-Tropsch Process.....	243
12.2.3	FT Fuel Properties .....	244

12.2.4	Emissions with Synthetic Fuel .....	244
12.3	Biodiesel .....	246
12.3.1	Introduction .....	246
12.3.2	Manufacturing Process .....	247
12.3.3	Properties and Specifications.....	248
12.3.4	Biodiesel Emissions.....	249
12.3.5	Compatibility with Petroleum Diesel Engines .....	253
12.4	Dimethyl Ether.....	254
12.4.1	Introduction .....	254
12.4.2	Manufacture of DME.....	255
12.4.3	DME as Automotive Fuel .....	256
12.4.4	DME Engines .....	257
12.4.5	DME Fuel and Emissions .....	258
12.5	Natural Gas .....	259
12.5.1	Utilization of Natural Gas .....	259
12.5.2	Emission Comparison.....	260
	References.....	263

## **Part IV      Emission Control through Engine Design.....** 267

<i>Chapter 13</i>	Steps Toward the Modern Diesel Engine.....	269
13.1	Introduction.....	269
13.2	Reduction of Nitrogen Oxides .....	269
13.2.1	Injection Timing Retard.....	269
13.2.2	Intake Charge Cooling.....	270
13.2.3	Combined Effect of Injection Timing and Intake Charge Cooling.....	270
13.2.4	Combined Effect of Injection Timing Retard and Charge Air Cooling on Fuel Consumption .....	271
13.2.5	Effect of Injection Pressure on Fuel Consumption.....	271
13.3	Reduction of Particulate Matter .....	272
13.3.1	Reduction of Particulate Matter through Air Management .....	273
13.3.2	Reduction of Particulate Matter through Combustion System Design.....	282
13.3.3	Reduction of Particulate Matter through Oil Consumption Control .....	284
13.3.4	Reduction of Particulate Matter through the Fuel Injection System .....	286
	References.....	289

<i>Chapter 14</i>	Emerging Technologies and the Modern Diesel Engine.....	291
14.1	Introduction.....	291
14.2	A Platform for Future Heavy-Duty Diesels .....	291
14.3	Platform for Future Light-Duty Passenger Car Diesels .....	292
14.4	Platform for Future Light-Duty Truck Diesels .....	292
14.5	Technology Options for Modernizing Diesels .....	293
14.6	Fuel Injection System Technology Options .....	294
14.7	Combustion System Technology Options .....	299
14.8	Air Charging System Technology Options .....	303
14.9	Air Induction System Technology Options.....	305
14.10	Variable Valve Actuation Technology Options .....	307
14.11	Combined Charge Air and Variable Valve Actuation Technology Options.....	308
14.12	New Combustion Technology Option.....	311
14.13	Engine Accessories and Subsystem Component Technology Options .....	311
14.14	Concluding Remarks.....	314
	References.....	315

<i>Chapter 15</i>	Water Addition to Diesel Combustion .....	317
15.1	Addition of Water to Diesel Process .....	317
15.1.1	Methods of Water Addition .....	317
15.1.2	Impact on Combustion Process .....	318
15.2	Fumigation of Water into Intake Air .....	319
15.3	Direct Injection of Water.....	320
15.4	Fuel Emulsions.....	321
15.4.1	Types of Emulsions .....	321
15.4.2	Impact on Combustion and Engine Performance .....	322
15.4.3	Impact on Emissions.....	323
15.5	Practical Embodiments .....	324
15.5.1	Commercial Status.....	324
15.5.2	PuriNOx Emulsion .....	325
15.5.3	Wartsila Water Injection System.....	325
15.5.4	Pielstick Humid Air Motor .....	326
	References.....	326
<i>Chapter 16</i>	Exhaust Gas Recirculation in Diesel Engines .....	329
16.1	Introduction.....	329
16.2	Definition .....	329
16.3	EGR Configurations.....	330
16.4	System Components.....	335
16.5	EGR Cooling and EGR Coolers .....	336
16.6	EGR Control Strategy .....	338
16.7	Effects of EGR on Combustion Parameters and Emissions.....	339
16.8	Effect of EGR on Diesel Engine Wear and Durability.....	344
16.8.1	Introduction .....	344
16.8.2	Background.....	344
16.8.3	Discussion.....	345
16.9	Alternative In-Cylinder Technologies to EGR for low NOX in Diesel Engines: A Review....	347
16.9.1	Effect of Pilot Injection and Injection Rate Shaping.....	347
16.10	Effect of Intake Charge Air Cooling .....	348
16.11	Effect of Injection Timing Retard .....	348
16.12	Issues Related to EGR Control Systems .....	348
16.12.1	Material Buildup within EGR Systems .....	349
16.12.2	EGR Contaminants .....	349
16.12.3	Engine Durability .....	349
16.12.4	Application/Test Cycle .....	349
16.12.5	EGR Cooler Design .....	349
16.12.6	EGR System Packaging .....	350
16.12.7	EGR Valve Control Considerations .....	350
16.12.8	Piping.....	350
16.13	Demonstration of Low NOx and PM Using EGR and a Passive Trap System.....	350
	References.....	352
<i>Chapter 17</i>	Controls for Modern Diesel Engines .....	355
17.1	Introduction.....	355
17.2	Background .....	355
17.3	Basic Operating Principles of the Control System .....	356
17.4	Variation in Closed-Loop Control Systems .....	356
17.5	Variation in Open-Loop Control Systems.....	356
17.6	The New Principle in Control Systems—A Model-Based Approach.....	357
17.6.1	EGR System Elements .....	357
17.6.2	Some Principles of Modeling .....	358
17.6.3	Discrete and Continuous Models.....	358
17.6.4	Data Conversion and Diagnostics Models.....	359

17.7	Challenges in Engine Control Systems.....	361
17.8	Neural Networks .....	361
17.9	Conclusion .....	363
	References.....	363
<b>Part V</b>	<b>Exhaust Gas Aftertreatment.....</b>	<b>365</b>
<i>Chapter 18</i>	Emission Control Catalysts.....	367
18.1	Overview .....	367
18.1.1	Background.....	367
18.1.2	Catalytic Reactors.....	368
18.1.3	Conversion of Pollutants: Basic Terms.....	369
18.2	Catalyst Fundamentals .....	370
18.2.1	Introduction .....	370
18.2.2	Conversion Rate in Heterogeneous Catalyst .....	372
18.2.3	Catalyst Deactivation.....	375
18.3	Cellular Monolith Substrates .....	377
18.3.1	Catalyst Substrates.....	377
18.3.2	Cellular Properties of Monoliths .....	378
18.3.3	Substrate Configuration and Performance .....	379
18.3.4	Catalyst Pressure Drop .....	379
18.4	Ceramic Catalyst Substrates .....	380
18.4.1	Introduction .....	380
18.4.2	Material Characterization Parameters .....	381
18.4.3	Cordierite .....	383
18.4.4	Commercial Substrates .....	383
18.5	Metallic Catalyst Substrates.....	384
18.5.1	Introduction .....	384
18.5.2	Substrate Materials .....	385
18.5.3	Substrate Designs .....	386
18.6	Catalytic Coating and Materials.....	389
18.6.1	Catalyst Washcoats .....	389
18.6.2	Aluminum Oxide .....	391
18.6.3	Silicon Oxide .....	392
18.6.4	Cerium Dioxide .....	392
18.6.5	Titanium Dioxide.....	392
18.6.6	Zirconium Oxide .....	392
18.6.7	Zeolites .....	392
18.7	Catalytic Converters.....	393
18.7.1	Introduction .....	393
18.7.2	Packaging Materials .....	394
18.7.3	Canning Methods.....	396
18.7.4	Header Design .....	398
18.7.5	Catalytic Mufflers .....	399
	References.....	400
<i>Chapter 19</i>	Diesel Catalysts .....	403
19.1	Overview .....	403
19.1.1	Catalyst Technologies.....	403
19.1.2	Diesel Oxidation Catalyst.....	404
19.1.3	NO <sub>x</sub> Reduction Catalysts .....	405
19.2	Diesel Oxidation Catalyst .....	407
19.2.1	Reactions in Diesel Oxidation Catalyst.....	407
19.2.2	Emissions Performance .....	408
19.2.3	Sulfate Formation .....	413

19.2.4	Catalysts and Configurations.....	416
19.3	Selective Catalytic Reduction.....	416
19.3.1	Introduction .....	416
19.3.2	Reductants and Catalytic Reactions .....	416
19.3.3	Catalysts .....	418
19.3.4	Stationary SCR Systems.....	421
19.3.5	SCR Systems for Mobile Engines .....	422
19.4	Lean NO <sub>x</sub> Catalyst.....	426
19.4.1	Selective Reduction of NO <sub>x</sub> by Hydrocarbons .....	426
19.4.2	Catalysts .....	427
19.4.3	Advanced Catalyst Systems.....	429
19.4.4	Diesel Engine Experience.....	432
19.5	NO <sub>x</sub> Adsorbers.....	432
19.5.1	NO <sub>x</sub> Adsorber Concept .....	432
19.5.2	Performance and Operation.....	436
19.5.3	Diesel Engine Systems .....	440
19.6	Commercial Catalyst Technologies .....	445
19.6.1	Introduction .....	445
19.6.2	Light-Duty Engines .....	446
19.6.3	Heavy-Duty Engines.....	448
19.7	Deactivation of Diesel Catalyst.....	450
19.7.1	Catalyst Durability.....	450
19.7.2	Thermal Degradation.....	451
19.7.3	Poisoning .....	451
	References.....	453
<i>Chapter 20</i>	<i>Diesel Particulate Filters.....</i>	<i>459</i>
20.1	Introduction.....	459
20.2	Principle of Operation.....	460
20.2.1	Filter Configuration .....	460
20.2.2	Filtration Mechanisms.....	460
20.2.3	Regeneration.....	462
20.3	DPF Performance.....	462
20.3.1	Particle Mass.....	462
20.3.2	Particle Numbers .....	463
20.4	Commercial Status.....	464
20.5	Diesel Filter Regeneration .....	465
20.5.1	Oxidation of Diesel Soot .....	465
20.5.2	Regeneration as an Equilibrium Process .....	466
20.5.3	Determination of Balance Temperature.....	469
20.5.4	Regeneration Methods .....	470
	References.....	471
<i>Chapter 21</i>	<i>Diesel Filter Materials .....</i>	<i>473</i>
21.1	Overview .....	473
21.1.1	Material Requirements .....	473
21.1.2	Types of Materials .....	474
21.2	Wall-Flow Monoliths .....	477
21.2.1	Monolith Construction.....	477
21.2.2	Monolith Characterization Parameters .....	478
21.2.3	Commercial Materials .....	482
21.2.4	Pressure Drop .....	488
21.2.5	Canning .....	489
21.3	Ceramic Fibers and Cartridges.....	489
21.3.1	Fiber Materials.....	489
21.3.2	Filtration Mechanism.....	490

21.3.3	Filter Cartridges.....	490
21.3.4	Advantages and Disadvantages of Fiber Filters .....	491
21.3.5	Example Design: Nextel Fiber Cartridges.....	491
	References.....	493
<i>Chapter 22</i>	Diesel Filter Systems .....	497
22.1	Overview .....	497
22.1.1	Design Considerations.....	497
22.1.2	Classification of Systems.....	497
22.1.3	Regeneration Strategy, Durability and Reliability.....	498
22.1.4	Future Trends.....	499
22.2	Catalyzed Diesel Filters .....	500
22.2.1	Introduction .....	500
22.2.2	Filter Design .....	500
22.2.3	Catalyst Systems.....	501
22.2.4	Emission Performance.....	502
22.2.5	Regeneration and Pressure Drop .....	505
22.2.6	Durability.....	507
22.3	CRT Filter .....	508
22.3.1	Principle of Operation .....	508
22.3.2	Application Limits.....	510
22.3.3	Filter System Design .....	511
22.3.4	Performance.....	512
22.3.5	Experience and Commercial Status.....	513
22.3.6	SCRT System.....	514
22.4	Filters with Fuel Additives .....	514
22.4.1	Fuel Additives.....	514
22.4.2	Catalytic Metals .....	515
22.4.3	Peugeot Filter System.....	517
22.4.4	Fiber Filters with Fuel Additives .....	519
22.5	Electrically Regenerated Filters .....	521
22.5.1	Electric Regeneration .....	521
22.5.2	Off-Board Regenerated Filters .....	522
22.5.3	Shore Power Regenerated Filters.....	523
22.5.4	Filters with On-Board Regeneration.....	525
22.6	Filters with Fuel Burners .....	527
22.6.1	Introduction .....	527
22.6.2	Full-flow Filter Systems .....	528
22.7	Microwave-Regenerated Filters .....	530
22.7.1	Microwave Heating.....	530
22.7.2	Diesel Filter Experience .....	532
	References.....	534
<i>Chapter 23</i>	Plasma Exhaust Treatment.....	537
23.1	Introduction.....	537
23.2	Nonthermal Plasma .....	538
23.2.1	What Is Plasma? .....	538
23.2.2	Plasma Generators .....	538
23.2.3	Energy Efficiency .....	539
23.3	Chemical Reactions .....	540
23.3.1	Plasma Chemistry .....	540
23.3.2	NO Reduction by Plasma .....	541
23.3.3	NO Oxidation .....	542
23.3.4	HC Oxidation.....	543

23.4	Plasma Catalysts .....	543
23.4.1	DeNOx Catalyst.....	543
23.4.2	SCR (Urea) Catalyst.....	544
23.5	Particulate Matter Control by Plasma .....	544
23.5.1	PM Oxidation by Plasma.....	544
23.5.2	Single-Stage Packed-Bed Plasma Reactor .....	545
23.5.3	Two-Stage Reactor: NTP-DPF Configuration .....	546
23.6	Future Issues .....	546
	References.....	547
<b>Index.....</b>		<b>549</b>
<b>About the Authors.....</b>		<b>563</b>