

# Contents

<b>Preface .....</b>	<b>xi</b>
<b>Chapter 1. Optical Engines.....</b>	<b>1</b>
1.1 Introduction.....	1
1.2 Optical Access .....	1
1.2.1 Optical Access Through the Cylinder Head.....	2
1.2.2 Optical Access Through the Piston .....	4
1.2.3 Optical Access Through the Sides.....	6
1.3 Endoscopic Access.....	7
1.4 Optical Materials.....	8
1.5 Operation of Optical Engines.....	9
References.....	10
<b>Chapter 2. Introduction to Laser-Based Optical Instruments .....</b>	<b>13</b>
2.1 Overview of Laser-Based Optical Instruments .....	13
2.2 Lasers.....	16
2.2.1 High-Energy Pulsed Lasers.....	17
2.2.2 High-Repetition Pulsed Lasers.....	18
2.2.3 Continuous Wave Lasers .....	19
2.3 Laser Beam Delivery and Focusing.....	21
2.3.1 Gaussian Laser Beam .....	21
2.3.2 Focusing of a Gaussian Laser Beam.....	22
2.3.3 Laser Sheet Optics .....	25
2.4 Optics and Photodetection Systems.....	26
2.4.1 Optics .....	26
2.4.2 Photon Detectors and Charge-Coupled Device (CCD) Cameras .....	32
2.4.3 High-Speed Imaging.....	36
2.5 Image Processing and Calibration.....	37
2.6 Summary.....	39
References.....	40
Further Reading.....	40
Websites .....	40

**Chapter 3. Fundamentals of Laser Spectroscopic Techniques..... 41**

3.1	Introduction.....	41
3.2	Fundamentals of Molecular Spectroscopy.....	41
3.2.1	Internal Energy of a Molecule .....	41
3.2.2	Population of Energy Levels.....	48
3.3	Raman and Rayleigh Scattering .....	49
3.3.1	Rayleigh Scattering and Its Measurement .....	49
3.3.2	Raman Scattering Spectrum.....	53
3.3.3	Measurement of Raman Scattering.....	58
3.4	Laser-Induced Fluorescence.....	61
3.5	Comparison of LRS, SRS, and LIF.....	67
3.6	Summary.....	69
	References.....	70
	Further Reading.....	70

**Chapter 4. Principle and Application of LDA and PIV for In-Cylinder Flow Measurements ..... 71**

4.1	Introduction.....	71
4.2	Laser Doppler Anemometry .....	71
4.2.1	The Principle of Laser Doppler Anemometry .....	71
4.2.2	Laser and Transmitting Optics .....	73
4.2.3	Light Collection System.....	75
4.2.4	Signal Processing .....	77
4.2.5	Discrimination of Flow Direction by Frequency Shifting....	78
4.2.6	Seeding and Particles .....	79
4.2.7	Accuracy .....	81
4.2.8	Advanced LDA Systems.....	82
4.2.9	Data Analysis of In-Cylinder Flows.....	84
4.2.10	Applications of LDA to IC Engines.....	90
4.3	Particle Image Velocimetry (PIV) .....	92
4.3.1	Principle of Particle Image Velocimetry .....	92
4.3.2	Operation of the Digital PIV System .....	94
4.3.3	Lasers and Light Sheets .....	95
4.3.4	Imaging Optics and Perspective Errors.....	97
4.3.5	Evaluation of Particle Image Displacement Vectors.....	99
4.3.6	Seeding Particles.....	103
4.3.7	Optimization of a PIV System .....	104
4.3.8	Postprocessing of PIV Data.....	107
4.3.9	Advanced PIV Systems.....	109
4.3.10	PIV Measurements in IC Engines.....	111

4.4	Summary.....	128
	References.....	129
<b>Chapter 5. In-Cylinder Fuel and Combustion Specie Measurement by Laser-Induced Fluorescence.....133</b>		
5.1	Introduction.....	133
5.2	Fuel Vapor Concentration Measurement by PLIF .....	133
	5.2.1 Principle of Operation .....	133
	5.2.2 Selection of Fluorescence Tracers .....	135
	5.2.3 Experimental Setup of PLIF .....	137
	5.2.4 Calibration of PLIF Images .....	138
	5.2.5 In-Cylinder Fuel Distribution Measurements by PLIF .....	139
5.3	Visualization of Combustion Species by PLIF.....	144
	5.3.1 Introduction.....	144
	5.3.2 Experimental Considerations .....	145
	5.3.3 PLIF Measurements of OH.....	148
	5.3.4 PLIF Measurements of NO.....	150
	5.3.5 Visualization of Formaldehyde by PLIF .....	153
5.4	Imaging of Water Vapor and CO by the Two-Photon LIF Technique.....	156
5.5	Summary.....	160
	References.....	160
<b>Chapter 6. Fuel and Mixture Composition Measurement by Raman and Rayleigh Scattering Techniques .....165</b>		
6.1	Introduction.....	165
6.2	Fuel Concentration Measurement by Laser Rayleigh Scattering .....	165
	6.2.1 Principle of Operation .....	166
	6.2.2 Implementation of LRS.....	167
	6.2.3 Minimization of Background Light in LRS.....	168
	6.2.4 Filtered Rayleigh Scattering.....	169
	6.2.5 Application of LRS to IC Engines .....	171
6.3	Measurement of Mixture Composition by Spontaneous Raman Scattering.....	173
	6.3.1 Introduction.....	173
	6.3.2 Principle of Operation .....	174
	6.3.3 Experimental Setup of SRS.....	176
	6.3.4 Background Radiation and Signal-to-Noise Ratio.....	179
	6.3.5 Data Analysis and Calibration.....	181
	6.3.6 Applications of the SRS Scattering Technique to IC Engines .....	183

6.3.7	Multispecies Measurements by SRS in a CAI Combustion Engine .....	185
6.4	Summary .....	194
	References .....	194

**Chapter 7. Fuel Injection and Spray Characterization .....199**

7.1	Introduction .....	199
7.2	Direct Imaging of Spray and Droplets .....	199
7.3	Liquid Droplet Sizing by the Fraunhofer Diffraction Method .....	201
7.3.1	Fraunhofer Diffraction .....	201
7.3.2	Implementation of the Fraunhofer Diffraction Method .....	202
7.4	Droplet Sizing and Velocity Measurements by the Phase Doppler Particle Analyzer (PDPA) .....	206
7.4.1	The Principle of the PDPA .....	206
7.4.2	Implementation of the PDPA .....	210
7.4.3	Data Reduction and Presentation .....	213
7.4.4	Optimization of a PDPA System .....	216
7.4.5	Application of PDPA to IC Engines .....	219
7.5	Two-Dimensional Visualization of Spray Atomization by Mie Scattering and Laser-Induced Fluorescence (LIF) .....	220
7.5.1	Two-Dimensional Spray Imaging Through Mie Scattering or PLIF .....	220
7.5.2	Laser Sheet Droplet Sizing (LSD) by Combined Mie Scattering and LIF .....	222
7.6	Simultaneous Visualization of Fuel Vapor and Liquid Fuel by the Laser-Induced Exciplex Fluorescence Technique .....	223
7.6.1	Principle of Laser-Induced Exciplex Fluorescence Technique .....	223
7.6.2	Experimental Setup of LIEF .....	226
7.6.3	Quantitative Analysis of Fuel Vapor Concentration Using PLIEF .....	228
7.6.4	Application of PLIEF for In-Cylinder Fuel Visualization .....	228
7.6.5	Application of LIEF to In-Cylinder Diesel Spray Measurement .....	231
7.7	Summary .....	234
	References .....	235

**Chapter 8. Combustion Spectroscopy and Visualization Techniques .....241**

8.1	Introduction .....	241
8.2	Combustion Spectroscopy .....	241
8.2.1	Light Emission of Combustion .....	241

8.2.2	Light Absorption of Combustion Species .....	243
8.2.3	Detection of Emission and Absorption .....	243
8.2.4	Application of Light Emission and Absorption Techniques .....	246
8.3	Chemiluminescence Imaging.....	248
8.4	Schlieren and Shadowgraph Techniques for Nonluminous Flow and Combustion Visualization .....	251
8.5	Summary.....	255
	References.....	255
<b>Chapter 9. Gas Temperature Measurement .....</b>		<b>259</b>
9.1	Introduction.....	259
9.2	Radiation Thermometry .....	259
9.2.1	Principles of Radiation Thermometry .....	259
9.2.2	Implementation of Radiation Thermometry .....	263
9.3	Laser Rayleigh Scattering (LRS) Thermometry.....	270
9.3.1	Principle of Laser Rayleigh Thermometry.....	270
9.3.2	Implementation and Application of Rayleigh Thermometry .....	270
9.4	Temperature Measurement by Spontaneous Raman Scattering (SRS).....	272
9.4.1	Principle of Raman Thermometry .....	272
9.4.2	Implementation and Application of Raman Thermometry .....	278
9.5	Temperature Measurement by Coherent Anti-Stokes Raman Scattering (CARS).....	280
9.5.1	Principle of CARS Thermometry .....	280
9.5.2	Implementation of CARS Nitrogen Thermometry.....	282
9.5.3	CARS Measurements in IC Engines .....	285
9.6	Two-Dimensional Temperature Measurement by PLIF.....	287
9.6.1	Introduction to Fluorescence Thermometry.....	287
9.6.2	Monochromatic Fluorescence Thermometry.....	287
9.6.3	Two-Line Fluorescence Thermometry.....	290
9.7	Summary.....	299
	References.....	300
<b>Chapter 10. In-Cylinder Soot Concentration and Particle Size Measurement.....</b>		<b>305</b>
10.1	Introduction.....	305
10.2	The Two-Color Method.....	306
10.2.1	Principle of the Two-Color Method .....	306

10.2.2	Implementation of the Two-Color Method.....	309
10.2.3	Accuracy .....	316
10.2.4	Full-Field Two-Color Measurement.....	317
10.3	Soot Concentration Measurement by the Light-Extinction Method .....	322
10.3.1	Principle of the Light-Extinction Method .....	322
10.3.2	Implementation of the Light-Extinction Method.....	326
10.4	Laser-Induced Incandescence .....	330
10.4.1	Introduction.....	330
10.4.2	Soot Volume Fraction Measurement by LII .....	331
10.4.3	Soot Particle Sizing Using LII and Laser Scattering (LS) ...	338
10.4.4	Particle Sizing by Time-Resolved LII (TiRe-LII).....	340
10.4.5	Further Considerations of LII Techniques .....	343
	References.....	344
	<b>Index .....</b>	<b>349</b>
	<b>About the Author.....</b>	<b>359</b>