

Franz Mayinger (Editor)

# Optical Measurements

Techniques and Applications

With 264 Figures

Springer-Verlag  
Berlin Heidelberg New York  
London Paris Tokyo  
Hong Kong Barcelona Budapest

# Table of Contents

|                                                                                                             |          |
|-------------------------------------------------------------------------------------------------------------|----------|
| <b>Optical Probes – Potential and Applicability</b>                                                         | <b>1</b> |
| 1 Introduction . . . . .                                                                                    | 3        |
| 2 Applications and Potential . . . . .                                                                      | 5        |
| 3 Introduction to the Schlieren and Shadowgraph Method . . . . .                                            | 11       |
| 3.1 Survey . . . . .                                                                                        | 11       |
| 3.1.1 Basic Principle of the Schlieren Method . . . . .                                                     | 11       |
| 3.1.2 Principle of the Shadowgraph Method . . . . .                                                         | 12       |
| 3.2 Optical Interrelations . . . . .                                                                        | 13       |
| 3.2.1 Refractive Index and Temperature Field . . . . .                                                      | 13       |
| 3.2.2 The Deflection of Light in an Inhomogeneous Medium<br>(Spatially Variable Refractive Index) . . . . . | 14       |
| 3.3 The Transport Relations for Heat . . . . .                                                              | 16       |
| 3.4 The Model Boundary Layer . . . . .                                                                      | 16       |
| 3.5 Calculation of the Light Deflection in the Thermal Boundary .                                           | 18       |
| 3.5.1 General Calculation of the Screen Coordinate $y_L(y_0)$ .                                             | 18       |
| 3.5.2 Localisation of the Screen Coordinates . . . . .                                                      | 19       |

|                                                  |           |
|--------------------------------------------------|-----------|
| <b>Holography and Holographic Interferometry</b> | <b>25</b> |
|--------------------------------------------------|-----------|

|                                                           |    |
|-----------------------------------------------------------|----|
| 4 Fundamentals of Holography and Interferometry . . . . . | 27 |
| 4.1 Abstract . . . . .                                    | 27 |
| 4.2 Introduction . . . . .                                | 27 |
| 4.3 Principle of Holography . . . . .                     | 29 |
| 4.4 Simple Holographic Arrangement . . . . .              | 30 |
| 4.5 Holographic Interferometry . . . . .                  | 34 |
| 4.5.1 Double Exposure Technique . . . . .                 | 35 |
| 4.5.2 Real-Time Method . . . . .                          | 39 |
| 4.5.3 Evaluation of the Interferograms . . . . .          | 42 |

|         |                                                                                                           |    |
|---------|-----------------------------------------------------------------------------------------------------------|----|
| 4.6     | An Interference Method for Simultaneous Heat and Mass Transfer . . . . .                                  | 45 |
| 4.7     | Comparison with Classical Methods . . . . .                                                               | 50 |
| 5       | Holographic Interferometry . . . . .                                                                      | 51 |
| 5.1     | Introduction . . . . .                                                                                    | 51 |
| 5.2     | Components of a Holographic Interferometer . . . . .                                                      | 51 |
| 5.2.1   | Light Source . . . . .                                                                                    | 52 |
| 5.2.2   | Optical Table . . . . .                                                                                   | 53 |
| 5.2.3   | Shutter . . . . .                                                                                         | 53 |
| 5.2.4   | Beam Splitter . . . . .                                                                                   | 53 |
| 5.2.5   | Attenuation Filter . . . . .                                                                              | 53 |
| 5.2.6   | Beam Expander . . . . .                                                                                   | 54 |
| 5.2.7   | Mirrors, Lenses . . . . .                                                                                 | 55 |
| 5.2.8   | Recording Materials . . . . .                                                                             | 55 |
| 5.2.9   | Piezo Mirror . . . . .                                                                                    | 57 |
| 5.2.10  | Test Facility . . . . .                                                                                   | 58 |
| 5.3     | Evaluation of Interferograms . . . . .                                                                    | 59 |
| 5.3.1   | Theoretical Principles . . . . .                                                                          | 59 |
| 5.3.2   | Conclusions . . . . .                                                                                     | 63 |
| 5.3.3   | Calculation of Temperature and Concentration Distributions . . . . .                                      | 64 |
| 5.3.4   | Determination of the Local Heat Transfer Coefficient . . . . .                                            | 65 |
| 5.4     | Examples . . . . .                                                                                        | 65 |
| 5.4.1   | Determination of the Temperature Distribution in a Compact Plate Heat Exchanger with Plain Fins . . . . . | 65 |
| 5.4.1.1 | Description of the Test Section . . . . .                                                                 | 65 |
| 5.4.1.2 | Description of the Interferograms . . . . .                                                               | 66 |
| 5.4.2   | Analysing Axisymmetrical Temperature Fields . . . . .                                                     | 67 |
| 5.5     | Distinction of Holograms . . . . .                                                                        | 72 |
| 6       | Differential Interferometry . . . . .                                                                     | 75 |
| 6.1     | Introduction . . . . .                                                                                    | 75 |
| 6.2     | Differential Interferometer . . . . .                                                                     | 78 |
| 6.2.1   | Wollaston Prism (WP) . . . . .                                                                            | 78 |
| 6.2.1.1 | Double Refraction . . . . .                                                                               | 78 |
| 6.2.2   | Optical Setup of a Differential Interferometer . . . . .                                                  | 80 |
| 6.3     | Evaluation of Interferograms . . . . .                                                                    | 82 |
| 6.4     | Useful Techniques . . . . .                                                                               | 85 |
| 6.4.1   | Beam Expansion . . . . .                                                                                  | 86 |
| 6.4.2   | Use of a Wollaston Prism . . . . .                                                                        | 87 |
| 6.4.3   | Adjustment of a Differential Interferometer . . . . .                                                     | 87 |
| 6.4.4   | Recording . . . . .                                                                                       | 88 |

|       |                                                                                                                                                    |     |
|-------|----------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 6.5   | Features and Applications . . . . .                                                                                                                | 88  |
| 7     | Pulsed Laser Holography . . . . .                                                                                                                  | 91  |
| 7.1   | Introduction . . . . .                                                                                                                             | 91  |
| 7.1.1 | The Holographic Image . . . . .                                                                                                                    | 91  |
| 7.1.2 | Types of Holograms . . . . .                                                                                                                       | 93  |
| 7.1.3 | Holography as an Optical Measurement Method . . . . .                                                                                              | 96  |
| 7.1.4 | Historical Development of the Holography . . . . .                                                                                                 | 96  |
| 7.2   | Elements of Holography . . . . .                                                                                                                   | 98  |
| 7.2.1 | Recording of Holograms . . . . .                                                                                                                   | 98  |
| 7.2.2 | Holographic Reconstruction . . . . .                                                                                                               | 101 |
| 7.2.3 | Recording Materials . . . . .                                                                                                                      | 101 |
| 7.3   | Optical Arrangement for the Pulsed Laser Holography . . . . .                                                                                      | 103 |
| 7.3.1 | The Pulsed Laser . . . . .                                                                                                                         | 104 |
| 7.3.2 | Selection of the Optical Components . . . . .                                                                                                      | 104 |
| 7.3.3 | Adjusting the Holographic Camera . . . . .                                                                                                         | 106 |
| 7.4   | Example of Application: Spray Characterization . . . . .                                                                                           | 107 |
| 7.4.1 | Statement of the Problem . . . . .                                                                                                                 | 107 |
| 7.4.2 | Visualization of the Spray Flow . . . . .                                                                                                          | 108 |
|       | 7.4.2.1 Single Pulsed Holograms for the Measurement<br>of the Spray Geometry, Drop Size and Drop<br>Distribution in the Injection Volume . . . . . | 108 |
|       | 7.4.2.2 Double Pulsed Holograms for the Measure-<br>ment of Droplet Velocities and Trajectories . . . . .                                          | 109 |
| 7.4.3 | Results . . . . .                                                                                                                                  | 112 |
| 8     | Evaluation of holograms by digital image processing . . . . .                                                                                      | 115 |
| 8.1   | Introduction . . . . .                                                                                                                             | 115 |
| 8.1.1 | Digitalization of a Picture . . . . .                                                                                                              | 115 |
| 8.1.2 | Grey Value Pictures . . . . .                                                                                                                      | 116 |
| 8.1.3 | Operations with Grey Value Images . . . . .                                                                                                        | 118 |
| 8.2   | The Digital Image Processing System . . . . .                                                                                                      | 123 |
| 8.2.1 | Scanning of Holographic Images . . . . .                                                                                                           | 123 |
|       | 8.2.1.1 Scanning of In-Line Holograms . . . . .                                                                                                    | 124 |
|       | 8.2.1.2 Scanning of Off-Axis-Holograms . . . . .                                                                                                   | 125 |
| 8.2.2 | Setup of the Digital Image Processing System . . . . .                                                                                             | 125 |
| 8.3   | Image Processing of Holographic Reconstructions . . . . .                                                                                          | 127 |
| 8.3.1 | Filtering Operations, Image Identification, and Focus-<br>ing Criteria . . . . .                                                                   | 128 |
| 8.3.2 | Measuring Algorithms . . . . .                                                                                                                     | 132 |
| 8.4   | Evaluation of Single Pulsed Holograms . . . . .                                                                                                    | 134 |
| 8.4.1 | Spray Form (Spray Angle, Break-Up Length) . . . . .                                                                                                | 135 |
| 8.4.2 | Drop Size and Drop Distribution . . . . .                                                                                                          | 135 |
| 8.5   | Evaluation of Double Pulsed Holograms . . . . .                                                                                                    | 139 |

|       |                                                      |     |
|-------|------------------------------------------------------|-----|
| 8.5.1 | Algorithms to Recognize Double Exposures of Droplets | 139 |
| 8.5.2 | Drop Velocity and Drop Trajectory . . . . .          | 145 |
| 8.6   | Evaluation of Interferograms . . . . .               | 147 |

## **Techniques Based on Light Scattering 157**

|        |                                                             |     |
|--------|-------------------------------------------------------------|-----|
| 9      | Light Scattering . . . . .                                  | 159 |
| 9.1    | Introduction . . . . .                                      | 159 |
| 9.2    | Scattering Processes . . . . .                              | 160 |
| 9.2.1  | Interaction of Light and Matter . . . . .                   | 160 |
| 9.2.2  | Elastic Scattering . . . . .                                | 163 |
| 9.2.3  | Inelastic Scattering . . . . .                              | 164 |
| 9.3    | Light Scattering Techniques in Heat Transfer . . . . .      | 166 |
| 9.3.1  | Mie Scattering . . . . .                                    | 166 |
| 9.3.2  | Rayleigh Scattering . . . . .                               | 168 |
| 9.3.3  | Raman Scattering . . . . .                                  | 169 |
| 9.3.4  | Laser Induced Fluorescence (LIF) . . . . .                  | 172 |
| 9.3.5  | Absorption . . . . .                                        | 174 |
| 9.4    | Concluding Remarks . . . . .                                | 176 |
| 10     | Laser-Doppler Velocimetry (LDV) . . . . .                   | 179 |
| 10.1   | Introduction . . . . .                                      | 179 |
| 10.2   | Principles of LDV . . . . .                                 | 179 |
| 10.3   | Optics . . . . .                                            | 180 |
| 10.3.1 | Basic Typs of LDV Optical Setups . . . . .                  | 180 |
| 10.3.2 | Optical Elements of a Fringe Mode LDV . . . . .             | 182 |
| 10.4   | Seeding Particles . . . . .                                 | 187 |
| 10.5   | Signal Processing . . . . .                                 | 188 |
| 10.5.1 | General Considerations . . . . .                            | 188 |
| 10.5.2 | Types of Signal Processing Systems . . . . .                | 190 |
| 10.6   | Application of LDV . . . . .                                | 191 |
| 10.6.1 | Applicability . . . . .                                     | 191 |
| 10.6.2 | Examples for Application of a LDV system . . . . .          | 191 |
| 11     | Dynamic Light Scattering . . . . .                          | 195 |
| 11.1   | Introduction . . . . .                                      | 195 |
| 11.2   | Overview . . . . .                                          | 195 |
| 11.3   | Light Scattering Theory . . . . .                           | 198 |
| 11.3.1 | Scattering Geometry. Assumptions . . . . .                  | 199 |
| 11.3.2 | Temporal and Spatial Behaviour of Scattered Light . . . . . | 200 |
| 11.3.3 | Correlation Functions . . . . .                             | 202 |
| 11.3.4 | Hydrodynamic Fluctuation Theory . . . . .                   | 205 |
| 11.4   | Experimental Methods . . . . .                              | 208 |
| 11.4.1 | Homodyne Method . . . . .                                   | 208 |

|          |                                                                                          |     |
|----------|------------------------------------------------------------------------------------------|-----|
| 11.4.2   | Heterodyne Method . . . . .                                                              | 211 |
| 11.5     | Measurement of Thermal Diffusivity . . . . .                                             | 212 |
| 12       | Raman Scattering . . . . .                                                               | 215 |
| 12.1     | Introduction . . . . .                                                                   | 215 |
| 12.2     | Theoretical Basics of Raman Spectroscopy . . . . .                                       | 216 |
| 12.2.1   | Concentration Measurements . . . . .                                                     | 218 |
| 12.2.2   | Temperature Measurement . . . . .                                                        | 221 |
| 12.2.2.1 | General Considerations . . . . .                                                         | 221 |
| 12.2.2.2 | Thermometry by Rotational Raman Spectroscopy . . . . .                                   | 222 |
| 12.2.2.3 | Thermometry by Vibrational Raman Spectroscopy . . . . .                                  | 227 |
| 12.3     | Experimental Setup . . . . .                                                             | 230 |
| 12.3.1   | Laser . . . . .                                                                          | 231 |
| 12.3.2   | Focussing and Collection Lenses . . . . .                                                | 234 |
| 12.3.3   | Spectral Frequency Selection . . . . .                                                   | 234 |
| 12.3.4   | Photon Converters . . . . .                                                              | 235 |
| 12.3.5   | Data Acquisition and Control . . . . .                                                   | 236 |
| 12.4     | Selected Applications . . . . .                                                          | 237 |
| 12.5     | Concluding Remarks . . . . .                                                             | 241 |
| 13       | Laser induced Fluorescence . . . . .                                                     | 243 |
| 13.1     | Introduction . . . . .                                                                   | 243 |
| 13.2     | Basic Principles of Laser Induced Fluorescence . . . . .                                 | 245 |
| 13.2.1   | General Considerations . . . . .                                                         | 245 |
| 13.2.2   | Concentration Measurement . . . . .                                                      | 250 |
| 13.2.3   | Temperature Measurement . . . . .                                                        | 251 |
| 13.3     | Experimental Setup and Procedures . . . . .                                              | 253 |
| 13.3.1   | Experimental Setup . . . . .                                                             | 253 |
| 13.3.2   | Experimental and Evaluation Procedures . . . . .                                         | 258 |
| 13.4     | Selected Applications . . . . .                                                          | 263 |
| 13.5     | Concluding Remarks . . . . .                                                             | 271 |
| 14       | Absorption . . . . .                                                                     | 273 |
| 14.1     | Introduction . . . . .                                                                   | 273 |
| 14.2     | Line Spectra . . . . .                                                                   | 274 |
| 14.2.1   | Position . . . . .                                                                       | 274 |
| 14.2.2   | Shape and Width . . . . .                                                                | 275 |
| 14.2.3   | Line Strength . . . . .                                                                  | 282 |
| 14.3     | Experimental Techniques . . . . .                                                        | 285 |
| 14.3.1   | Overview . . . . .                                                                       | 285 |
| 14.3.2   | Experimental Examples . . . . .                                                          | 290 |
| 14.3.2.1 | In Situ Measurements of Ammonia Concentration in Industrial Combustion Systems . . . . . | 290 |

|          |                                                                                         |     |
|----------|-----------------------------------------------------------------------------------------|-----|
| 14.3.2.2 | Fast Temperature Measurements with Tunable Diode Lasers . . . . .                       | 294 |
| 14.3.2.3 | Harmonic Detection Techniques for the Measurement of Small Absorptions . . . . .        | 297 |
| 14.3.2.4 | Oxygen Detection with Near Infrared Diode Lasers and Integrative Spectroscopy . . . . . | 304 |
| 14.3.2.5 | In Situ Determination of Free Radicals in Flames . . . . .                              | 307 |

## **Light Emission Techniques 313**

|        |                                                            |     |
|--------|------------------------------------------------------------|-----|
| 15     | Pyrometry and Thermography . . . . .                       | 315 |
| 15.1   | Introduction . . . . .                                     | 315 |
| 15.2   | Temperature Radiation . . . . .                            | 316 |
| 15.3   | Method of Transmission . . . . .                           | 323 |
| 15.4   | Radiation Receiver (Detector) . . . . .                    | 326 |
| 15.5   | Thermal Cameras – Thermography Image Systems . . . . .     | 329 |
| 15.6   | Pyrometers . . . . .                                       | 331 |
| 15.6.1 | Classification According to Construction Types . . . . .   | 335 |
| 15.6.2 | Filament and Quotient Pyrometers . . . . .                 | 336 |
| 15.6.3 | IR Recording Heads . . . . .                               | 337 |
| 15.7   | Error Potential . . . . .                                  | 337 |
| 15.7.1 | Error Sources During Recording . . . . .                   | 337 |
| 15.7.2 | Equipment Error . . . . .                                  | 340 |
| 15.7.3 | Problems with Thermograph Readings . . . . .               | 340 |
| 15.8   | Appendix . . . . .                                         | 342 |
| 15.8.1 | Important Constants . . . . .                              | 342 |
| 15.8.2 | Further Information and Tables . . . . .                   | 342 |
| 16     | Self Fluorescence . . . . .                                | 349 |
| 16.1   | Introduction . . . . .                                     | 349 |
| 16.2   | Basic Principles of Self Fluorescence . . . . .            | 350 |
| 16.3   | Experimental Setup and Procedures . . . . .                | 357 |
| 16.4   | Selected Applications in Hydrogen-Air Combustion . . . . . | 361 |
| 16.4.1 | Unstationary Combustion Processes . . . . .                | 361 |
| 16.4.2 | Stationary Flames . . . . .                                | 363 |
| 16.5   | Concluding Remarks . . . . .                               | 364 |

## **Tomography 369**

|      |                                                                 |     |
|------|-----------------------------------------------------------------|-----|
| 17   | Tomographic Measurement and Reconstruction Techniques . . . . . | 371 |
| 17.1 | Introduction . . . . .                                          | 371 |
| 17.2 | Measurement Methods . . . . .                                   | 372 |

|          |                                                     |     |
|----------|-----------------------------------------------------|-----|
| 17.2.1   | Absorption Methods . . . . .                        | 374 |
| 17.2.1.1 | Electromagnetic Waves . . . . .                     | 375 |
| 17.2.1.2 | Corpuscular Radiation . . . . .                     | 375 |
| 17.2.1.3 | Sound Waves . . . . .                               | 376 |
| 17.2.2   | Interferometric Methods . . . . .                   | 377 |
| 17.2.2.1 | Coherent Light Waves . . . . .                      | 378 |
| 17.2.2.2 | Sound Waves . . . . .                               | 379 |
| 17.2.3   | Infrared and Nuclear Magnetic Resonance Imaging . . | 380 |
| 17.2.4   | Irradiation Techniques . . . . .                    | 381 |
| 17.2.4.1 | Three-Dimensional Irradiation . . . . .             | 383 |
| 17.3     | Mathematical Reconstruction Methods . . . . .       | 384 |
| 17.3.1   | Algebraic Reconstruction Methods . . . . .          | 387 |
| 17.3.1.1 | Matrix Methods . . . . .                            | 387 |
| 17.3.1.2 | Iterative Series Expansion . . . . .                | 389 |
| 17.3.2   | Explicit Reconstruction Methods . . . . .           | 396 |
| 17.3.2.1 | Fourier Transform Method . . . . .                  | 396 |
| 17.3.2.2 | Analytical Solution of Integral Equations . . .     | 401 |
| 17.3.3   | Comparison of Reconstruction Methods . . . . .      | 402 |
| 17.4     | Implementations . . . . .                           | 406 |
| 17.4.1   | Tomographic Measurements in Gases . . . . .         | 408 |
| 17.4.2   | Measurements in Liquids . . . . .                   | 413 |
| 17.4.3   | Tomographic Measurements in Multiphase Systems . .  | 420 |
|          | Nomenclatur . . . . .                               | 425 |
|          | References . . . . .                                | 437 |
|          | Index . . . . .                                     | 453 |