

CONTENTS

PREFACE TO THE FIRST EDITION	xiii
PREFACE TO THE SECOND EDITION	xiv
1 INTERPRETATION OF FLOW VISUALIZATION	1
1.1 Introduction	1
1.2 Critical Points in Flow Patterns	1
1.3 Relationship between Streamlines, Pathlines, and Streaklines	9
1.4 Sectional Streamlines	15
1.5 Bifurcation Lines	16
1.6 Interpretation of Unsteady Flow Patterns with the Aid of Streaklines and Streamlines	18
1.7 Concluding Remarks	23
1.8 References	24
2 HYDROGEN BUBBLE VISUALIZATION	27
2.1 Introduction	27
2.2 The Hydrogen Bubble Generation System	29
2.2.1 Safety	32
2.3 Bubble Probes	33
2.4 Lighting	37
2.5 Unique Applications	38
2.6 References	44
3 DYE AND SMOKE VISUALIZATION	47
3.1 Introduction	47
3.2 Flow Visualization in Water	48
3.2.1 Conventional dye	48
3.2.2 Laundry brightener	49
3.2.3 Milk	49
3.2.4 Fluorescent dye	49
3.2.5 Methods of dye injection	50

3.2.6	Rheoscopic fluid	52
3.2.7	Electrolytic precipitation	53
3.3	Flow Visualization in Air	57
3.3.1	Smoke tunnel	57
3.3.2	Smoke generator	57
3.3.3	Smoke-wire technique	59
3.3.4	Titanium tetrachloride	62
3.4	Photographic Equipment and Techniques	63
3.4.1	Lighting	63
3.4.2	Camera	66
3.4.3	Lens	70
3.4.4	Film	72
3.5	Cautionary Notes	73
3.6	References	76
4	MOLECULAR TAGGING VELOCIMETRY AND THERMOMETRY	79
4.1	Introduction	79
4.2	Properties of Photo-Sensitive Tracers	80
4.2.1	Photochromic dyes	80
4.2.2	Phosphorescent supramolecules	80
4.2.3	Caged dyes	83
4.3	Examples of Molecular Tagging Measurements	86
4.3.1	Phosphorescent supramolecules	87
4.3.2	Caged dye tracers	89
4.4	Image Processing and Experimental Accuracy	93
4.4.1	Line processing techniques	93
4.4.2	Grid processing techniques	96
4.4.3	Ray tracing	97
4.4.4	Molecular tagging thermometry	98
4.5	References	103
5	PLANAR IMAGING OF GAS PHASE FLOWS	107
5.1	Introduction	107
5.2	Planar Laser-Induced Fluorescence	109
5.2.1	Velocity tracking by laser-induced fluorescence	116
5.3	Rayleigh Imaging from Molecules and Particles	120
5.4	Filtered Rayleigh Scattering	124

5.5	Planar Doppler Velocimetry	132
5.6	Summary	137
5.7	References	137
6	DIGITAL PARTICLE IMAGE VELOCIMETRY	143
6.1	Quantitative Flow Visualization	143
6.2	DPIV Experimental Setup	144
6.3	Particle Image Velocimetry: A Visual Presentation	145
6.4	Image Correlation	146
6.4.1	Peak finding	149
6.4.2	Computational implementation in frequency space	150
6.5	Video Imaging	150
6.6	Post Processing	152
6.6.1	Outlier removal	152
6.6.2	Differentiable flow properties	153
6.6.3	Integrable flow properties	155
6.7	Sources of Error	155
6.7.1	Uncertainty due to particle image density	156
6.7.2	Uncertainty due to velocity gradients within the interrogation windows	156
6.7.3	Uncertainty due to different particle size imaging	157
6.7.4	Effects of using different sizes of interrogation windows	157
6.7.5	Mean-bias error removal	158
6.8	DPIV Applications	161
6.8.1	Investigation of vortex ring formation	161
6.8.2	A novel application for force prediction DPIV	161
6.8.3	DPIV and a CFD counterpart: Common ground	161
6.9	Conclusion	163
6.10	References	165
7	SURFACE TEMPERATURE SENSING WITH THERMOCHROMIC LIQUID CRYSTALS	167
7.1	Introduction	167
7.1.1	Properties of liquid crystals	168
7.1.2	Temperature calibration techniques	170
7.1.3	Convective heat transfer coefficient measurement techniques	170

7.2	Implementation	173	9	METHODS FOR COMPRESSIBLE FLOWS	227
7.2.1	Sensing sheet preparation	175	9.1	Introduction	227
7.2.2	Test surface illumination	176	9.2	Basic Optical Concepts	228
7.2.3	Image capture and reduction	178	9.3	Index of Refraction for a Gas	231
7.2.4	Calibration and measurement uncertainty	179	9.4	Light Ray Deflection and Retardation in a Refractive Field	233
7.3	Examples	182	9.5	Shadowgraph	235
7.3.1	Turbine cascade	182	9.6	Schlieren Method	241
7.3.2	Turbulent spot and boundary layer	183	9.7	Interferometry	244
7.3.3	Turbulent juncture flow	184	9.8	Interference	245
7.3.4	Particle image thermography	185	9.9	Mach-Zehnder Interferometer	248
7.4	References	186	9.10	Holography	252
8	PRESSURE AND SHEAR SENSITIVE COATINGS	191	9.11	Holographic Interferometry	254
8.1	Introduction	191	9.12	Applications	258
8.2	Pressure-Sensitive Paint	192	9.13	Summary	262
8.2.1	Obtaining and applying pressure-sensitive paint	195	9.14	References	264
8.2.2	Lamps	197	10	THREE-DIMENSIONAL IMAGING	267
8.2.3	Cameras	198	10.1	Introduction	267
8.2.4	Data reduction	200	10.2	Three-Dimensional Imaging Techniques	267
8.3	Shear-Sensitive Liquid Crystal Coating Method	202	10.3	Image Data Types	271
8.3.1	Color-change responses to shear	203	10.4	Laser Scanner Designs	272
8.3.2	Coating application	205	10.5	Discrete Laser Sheet Systems	273
8.3.3	Lighting and imaging	206	10.6	Double Scan Laser Sweep Systems	274
8.3.4	Data acquisition and analysis	207	10.7	Single Scan Laser Sweep Systems (Discrete)	278
8.3.5	Example: Visualization of transition and separation	209	10.8	Drum Scanners	280
8.3.6	Example: Application of shear vector method	212	10.9	Multiple Fixed Laser Sheets	282
8.4	Fringe Imaging Skin Friction Interferometry	214	10.10	Moving Laser Sheet Systems	284
8.4.1	Physical principles	214	10.11	Imaging Issues and Trade-Offs	285
8.4.2	Surface preparation	215	10.11.1	Position accuracy of laser sheets	285
8.4.3	Lighting	216	10.11.2	Illumination issues	286
8.4.4	Imaging	218	10.11.3	Sweeps versus sheets for CW lasers	287
8.4.5	Calibration	219	10.11.4	Optical components	288
8.4.6	Data reduction	219	10.11.5	Methods of control	289
8.4.7	Uncertainty	221	10.11.6	Operational considerations	290
8.4.8	Examples	222	10.11.7	Imaging devices	294
8.5	References	224	10.12	Detailed Example	295
			10.12.1	Control system design	298

10.13 Analysis and Display of Data	300	12.3.4 Contact tracking and convergence of simulations	357
10.13.1 Processing and analysis of data	300	12.3.5 Quantification of local shock properties	360
10.13.2 Methods of presentation and display	302	12.4 Conclusion	361
10.14 Concluding remarks	305	12.5 Appendix A: Pseudo-code to Extract the Discontinuity Curves .	362
10.15 References	305	12.6 References	365
11 QUANTITATIVE FLOW VISUALIZATION VIA FULLY RESOLVED FOUR-DIMENSIONAL IMAGING	311	COLOR PLATES AND FLOW GALLERY	367
11.1 Introduction	311	INDEX	423
11.2 Technical Considerations	313		
11.2.1 Laser induced fluorescence	313		
11.2.2 Beam scanning electronics	313		
11.2.3 Data acquisition system	316		
11.2.4 Signal levels	317		
11.2.5 Signal-to-noise ratio	322		
11.2.6 Spatial and temporal resolution	324		
11.2.7 Data processing	328		
11.3 Sample Applications	330		
11.3.1 Fine structure of turbulent scalar fields	330		
11.3.2 Assessment of Taylor's hypothesis	332		
11.3.3 Scalar imaging velocimetry	333		
11.3.4 Fractal scaling of turbulent scalar fields	333		
11.4 Further Information	335		
11.5 References	337		
12 VISUALIZATION, FEATURE EXTRACTION, AND QUANTIFICATION OF NUMERICAL VISUALIZATIONS OF HIGH-GRADIENT COMPRESSIBLE FLOWS	339		
12.1 Introduction	339		
12.1.1 Fundamental configuration	340		
12.2 Visualization Techniques	343		
12.2.1 Numerical analog of experimental techniques	343		
12.2.2 Smoothing and noise suppression	346		
12.2.3 Selection of variables for visualization	348		
12.3 Quantification of Shocks and Contacts	350		
12.3.1 One-dimensional example	350		
12.3.2 Algorithm	350		
12.3.3 Two-dimensional example	355		