

# CONTENTS

<b>PREFACE</b>	<b>v</b>
<b>1 INTERPRETATION OF FLOW VISUALIZATION</b>	<b>1</b>
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 Streak- lines and Streamlines . . . . .	18
1.7 Concluding Remarks . . . . .	23
1.8 References . . . . .	24
<b>2 HYDROGEN BUBBLE VISUALIZATION</b>	<b>27</b>
2.1 Introduction . . . . .	27
2.2 The Hydrogen Bubble Generating System . . . . .	29
2.3 Bubble Probes . . . . .	32
2.4 Lighting . . . . .	36
2.5 Unique Applications . . . . .	37
2.6 References . . . . .	41
<b>3 DYE AND SMOKE VISUALIZATION</b>	<b>43</b>
3.1 Introduction . . . . .	43
3.2 Flow Visualization in Water . . . . .	44
3.2.1 Conventional dye . . . . .	44
3.2.2 Laundry brightener . . . . .	45
3.2.3 Milk . . . . .	45
3.2.4 Fluorescent dye . . . . .	45
3.2.5 Methods of dye injection . . . . .	46
3.2.6 Rheoscopic fluid . . . . .	48
3.2.7 Electrolytic precipitation . . . . .	49

3.3	Flow Visualization in Air . . . . .	52
3.3.1	Smoke tunnel . . . . .	52
3.3.2	Smoke generator . . . . .	53
3.3.3	Smoke-wire technique . . . . .	54
3.3.4	Titanium tetrachloride . . . . .	57
3.4	Photographic Equipment and Techniques . . . . .	58
3.4.1	Lighting . . . . .	58
3.4.2	Camera . . . . .	61
3.4.3	Lens . . . . .	63
3.4.4	Film . . . . .	66
3.5	Cautionary Notes . . . . .	66
3.6	References . . . . .	69
<b>4</b>	<b>MOLECULAR TAGGING VELOCIMETRY</b>	<b>73</b>
4.1	Introduction . . . . .	73
4.2	Properties of Photo-Sensitive Tracers . . . . .	74
4.2.1	Photochromic dyes . . . . .	74
4.2.2	Phosphorescent supramolecules . . . . .	74
4.2.3	Caged dyes . . . . .	76
4.3	Examples of Molecular Tagging Measurements . . . . .	80
4.3.1	Phosphorescent supramolecules . . . . .	80
4.3.2	Caged dye tracers . . . . .	82
4.4	Image Processing and Experimental Accuracy . . . . .	86
4.4.1	Line processing techniques . . . . .	86
4.4.2	Grid processing techniques . . . . .	89
4.4.3	Ray tracing . . . . .	89
4.5	References . . . . .	90
<b>5</b>	<b>PLANAR LASER IMAGING</b>	<b>93</b>
5.1	Introduction . . . . .	93
5.2	Planar Laser-Induced Fluorescence . . . . .	95
5.3	Rayleigh Imaging from Molecules and Particles . . . . .	102
5.4	Filtered Rayleigh Scattering . . . . .	105
5.5	Planar Doppler Velocimetry . . . . .	111
5.6	Summary . . . . .	117
5.7	References . . . . .	118

<b>6</b>	<b>DIGITAL PARTICLE IMAGE VELOCIMETRY</b>	<b>123</b>
6.1	Quantitative Flow Visualization . . . . .	123
6.2	DPIV Experimental Setup . . . . .	124
6.3	Particle Image Velocimetry: A Visual Presentation . . . . .	125
6.4	Image Correlation . . . . .	126
6.4.1	Peak finding . . . . .	129
6.4.2	Computational implementation of DPIV in frequency space . . . . .	130
6.5	Video Imaging . . . . .	130
6.6	Post Processing . . . . .	132
6.6.1	Outlier removal . . . . .	132
6.6.2	Differentiable flow properties . . . . .	133
6.6.3	Integrable flow properties . . . . .	135
6.7	Sources of Error . . . . .	135
6.7.1	Uncertainty due to particle image density . . . . .	136
6.7.2	Uncertainty due to velocity gradients within the interro- gation windows . . . . .	136
6.7.3	Uncertainty due to different particle size imaging . . . . .	137
6.7.4	Effects of using different size interrogation windows . . . . .	137
6.7.5	Mean-bias error removal . . . . .	138
6.8	DPIV Applications . . . . .	141
6.8.1	Investigation of vortex ring formation. . . . .	141
6.8.2	A novel application for force prediction DPIV . . . . .	141
6.8.3	DPIV and a CFD counterpart: a common ground . . . . .	141
6.9	Conclusion . . . . .	143
6.10	References . . . . .	145
<b>7</b>	<b>SURFACE TEMPERATURE SENSING WITH THERMO- CHROMIC LIQUID CRYSTALS</b>	<b>149</b>
7.1	Introduction . . . . .	149
7.1.1	Calibration techniques . . . . .	150
7.1.2	Convective heat transfer coefficient measurement techniques . . . . .	151
7.2	Implementation . . . . .	155
7.2.1	Sensing sheet preparation . . . . .	155
7.2.2	Test surface illumination . . . . .	156
7.2.3	Data reduction . . . . .	157
7.2.4	Calibration . . . . .	159

7.2.5	Establishing uncertainty . . . . .	161
7.3	Examples . . . . .	161
7.3.1	Turbine cascade . . . . .	161
7.3.2	Turbulent spot and boundary layer . . . . .	162
7.3.3	Turbulent juncture flow . . . . .	163
7.4	Concluding Remarks . . . . .	165
7.5	References . . . . .	166
<b>8</b>	<b>PRESSURE AND SHEAR SENSITIVE COATINGS</b>	<b>169</b>
8.1	Introduction . . . . .	169
8.2	Pressure-Sensitive Paint . . . . .	170
8.2.1	Obtaining and applying pressure-sensitive paint . . . . .	173
8.2.2	Lamps . . . . .	175
8.2.3	Cameras . . . . .	176
8.2.4	Data reduction . . . . .	178
8.3	Shear-Sensitive Liquid Crystal Coating Method . . . . .	180
8.3.1	Color-change responses to shear . . . . .	181
8.3.2	Coating application . . . . .	183
8.3.3	Lighting and imaging . . . . .	184
8.3.4	Data acquisition and analysis . . . . .	185
8.3.5	Example: Visualization of transition and separation . . . . .	187
8.3.6	Example: Application of shear vector method . . . . .	190
8.4	Fringe Imaging Skin Friction Interferometry . . . . .	192
8.4.1	Physical principles . . . . .	192
8.4.2	Surface preparation . . . . .	193
8.4.3	Lighting . . . . .	194
8.4.4	Imaging . . . . .	196
8.4.5	Calibration . . . . .	197
8.4.6	Data reduction . . . . .	197
8.4.7	Uncertainty . . . . .	199
8.4.8	Examples . . . . .	200
8.5	References . . . . .	201
<b>9</b>	<b>METHODS FOR COMPRESSIBLE FLOWS</b>	<b>205</b>
9.1	Introduction . . . . .	205
9.2	Basic Optical Concepts . . . . .	206
9.3	Index of Refraction for a Gas . . . . .	209
9.4	Light Ray Deflection and Retardation in a Refractive Field . . . . .	211

9.5	Shadowgraph . . . . .	213
9.6	Schlieren Method . . . . .	219
9.7	Interferometry . . . . .	221
9.8	Interference . . . . .	224
9.9	Mach-Zehnder Interferometer . . . . .	226
9.10	Holography . . . . .	230
9.11	Holographic Interferometry . . . . .	232
9.12	Applications . . . . .	237
9.13	Summary . . . . .	240
9.14	References . . . . .	242
<b>10</b>	<b>THREE-DIMENSIONAL IMAGING</b>	<b>245</b>
10.1	Introduction . . . . .	245
10.2	3-D Imaging Techniques . . . . .	245
10.3	Image Data Types . . . . .	249
10.4	Laser Scanner Designs . . . . .	250
10.5	Discrete Laser Sheet Systems . . . . .	251
10.6	Double Scan Laser Sweep Systems . . . . .	252
10.7	Single Scan Laser Sweep Systems (Discrete) . . . . .	256
10.8	Drum Scanners . . . . .	258
10.9	Multiple Fixed Laser Sheets . . . . .	260
10.10	Moving Laser Sheet Systems . . . . .	262
10.11	Imaging Issues and Trade-Offs . . . . .	263
10.11.1	Position accuracy of laser sheets . . . . .	263
10.11.2	Illumination issues . . . . .	264
10.11.3	Sweeps versus sheets for CW lasers . . . . .	265
10.11.4	Optical components . . . . .	267
10.11.5	Methods of control . . . . .	268
10.11.6	Operational considerations . . . . .	269
10.11.7	Imaging devices . . . . .	272
10.12	Detailed Example . . . . .	273
10.12.1	Control system design . . . . .	276
10.13	Analysis and Display of Data . . . . .	279
10.13.1	Processing and analysis of data . . . . .	279
10.13.2	Methods of presentation and display . . . . .	280
10.14	Concluding remarks . . . . .	283
10.15	Acknowledgments . . . . .	283
10.16	References . . . . .	284

<b>11 QUANTITATIVE FLOW VISUALIZATION VIA FULLY-RESOLVED FOUR-DIMENSIONAL IMAGING</b>	<b>289</b>
11.1 Introduction . . . . .	289
11.2 Technical Considerations . . . . .	291
11.2.1 Laser induced fluorescence . . . . .	291
11.2.2 Beam scanning electronics . . . . .	291
11.2.3 Data acquisition system . . . . .	294
11.2.4 Signal levels . . . . .	295
11.2.5 Signal-to-noise ratio . . . . .	300
11.2.6 Spatial and temporal resolution . . . . .	302
11.2.7 Data processing . . . . .	306
11.3 Sample Applications . . . . .	308
11.3.1 Fine structure of turbulent scalar fields . . . . .	308
11.3.2 Assessment of Taylor's hypothesis . . . . .	310
11.3.3 Scalar imaging velocimetry . . . . .	311
11.3.4 Fractal scaling of turbulent scalar fields . . . . .	311
11.4 Further Information . . . . .	313
11.5 References . . . . .	315
<b>12 VISUALIZATION, FEATURE EXTRACTION AND QUANTIFICATION OF NUMERICAL VISUALIZATIONS OF HIGH GRADIENT COMPRESSIBLE FLOWS</b>	<b>317</b>
12.1 Introduction . . . . .	317
12.1.1 Fundamental configuration . . . . .	318
12.2 Visualization Techniques . . . . .	321
12.2.1 Numerical analog of experimental techniques . . . . .	321
12.2.2 Smoothing and noise suppression . . . . .	325
12.2.3 Selection of variables for visualization . . . . .	325
12.3 Quantification of Shocks and Contacts . . . . .	327
12.3.1 One-dimensional example . . . . .	328
12.3.2 Algorithm . . . . .	328
12.3.3 Two-dimensional example . . . . .	333
12.3.4 Contact tracking and convergence of simulations . . . . .	334
12.3.5 Quantification of local shock properties . . . . .	337
12.4 Conclusion . . . . .	339
12.5 References . . . . .	343
<b>COLOR PLATES AND FLOW GALLERY</b>	<b>345</b>