

Contents

| | | |
|----------|--|-----------|
| 1 | Fundamentals of Cavitation | 1 |
| 1.1 | Introduction | 1 |
| 1.2 | Process and Thresholds of Cavitation | 2 |
| 1.2.1 | Nucleation, Growth, Oscillation, Collapse, and Dissolution. | 2 |
| 1.2.2 | Nucleation and Collapse Thresholds | 3 |
| 1.3 | Cavitation Nuclei | 10 |
| 1.3.1 | Microcavity | 10 |
| 1.3.2 | Encapsulated Bubble | 12 |
| 1.3.3 | Phase-Shift Nanodroplet. | 14 |
| 1.3.4 | Other Micro-/Nanoscale Particles | 17 |
| 1.4 | Tensile and Energetic Cavitation. | 18 |
| 1.5 | Cavitation Bubble Dynamics | 19 |
| 1.5.1 | Free Gas Bubble Dynamics in a Free Field | 19 |
| 1.5.2 | Encapsulated Bubble Dynamics in a Free Field. | 21 |
| 1.5.3 | Bubble Dynamics Near an Interface | 24 |
| 1.5.4 | Bubble Dynamics in Constrained Vessel | 29 |
| 1.5.5 | Bubble Dynamics in Soft Tissue. | 35 |
| 1.6 | Summary | 42 |
| | References. | 43 |
| 2 | Cavitation Mapping | 47 |
| 2.1 | Introduction | 47 |
| 2.2 | Cavitation Mapping by High-Speed Photography | 49 |
| 2.2.1 | Single-Bubble Cavitation | 50 |
| 2.2.2 | Multiple-Bubble Cavitation | 52 |
| 2.2.3 | Cavitation in Microvessel. | 55 |
| 2.3 | Cavitation Mapping by Sonoluminescence and Sonochemiluminescence. | 58 |
| 2.3.1 | Mechanisms of SL and SCL. | 59 |
| 2.3.2 | Free Field | 65 |

| | | |
|----------|--|------------|
| 2.3.3 | Tissue–Fluid Interface | 66 |
| 2.3.4 | Bone–Fluid Interface | 68 |
| 2.3.5 | Microvessel | 69 |
| 2.3.6 | Bioreactor | 70 |
| 2.4 | ACD, PCD, and Doppler Methods | 73 |
| 2.4.1 | Acoustic Scattering and ACD | 74 |
| 2.4.2 | Acoustic Emission and PCD. | 77 |
| 2.4.3 | Frequency Shift Signal and Doppler | 82 |
| 2.5 | Precise Active Acoustic Mapping of Cavitation Bubbles | 85 |
| 2.5.1 | Ultrasound Line-by-Line Scanning Method | 85 |
| 2.5.2 | Repeatability and Feasibility. | 86 |
| 2.5.3 | Spatial and Temporal Cavitation Distributions | 87 |
| 2.6 | Ultrafast Active Cavitation Mapping with a Plane Wave Beam | 90 |
| 2.6.1 | Plane Wave DAS-Based UACM. | 91 |
| 2.6.2 | Plane Wave Adaptive Beamforming-Based UACM | 92 |
| 2.6.3 | Performance of UACM in a Free Field | 94 |
| 2.7 | Passive Cavitation Mapping | 100 |
| 2.7.1 | Time-Domain PCM. | 101 |
| 2.7.2 | Fourier-Domain PCM | 106 |
| 2.8 | Summary | 109 |
| | References. | 110 |
| 3 | Size Distribution of Cavitation Bubbles | 115 |
| 3.1 | Introduction | 115 |
| 3.2 | The Kinetics of Free Bubble Dissolution | 116 |
| 3.2.1 | Single-Component System | 116 |
| 3.2.2 | Two-Component System | 117 |
| 3.2.3 | Multi-component System | 120 |
| 3.3 | Sonoluminescence Method | 122 |
| 3.4 | PCD-Based Cavitation Noise Method | 124 |
| 3.5 | Void Rate Method by Shifting the Electromagnetic Resonant Frequency | 128 |
| 3.6 | ACD-Based Scattering Method | 132 |
| 3.7 | Wide-Beam ACD-Based Backscattering Method | 136 |
| 3.8 | Effects of Acoustic Pressure, Frequency, and Duration. | 139 |
| 3.8.1 | The Effect of Acoustic Pressure and Power | 140 |
| 3.8.2 | The Effect of Acoustic Frequency | 141 |
| 3.8.3 | The Effect of Acoustic Pulse Duration. | 141 |
| 3.9 | Bubble Size Distribution for Acoustic Droplet Vaporization. | 143 |
| 3.9.1 | The Principle | 143 |
| 3.9.2 | Experimental Methods | 144 |
| 3.9.3 | Typical Results. | 146 |

| | | |
|----------|---|------------|
| 3.10 | Considering Vapor Condensation for PNE-S/PNE-DS | 146 |
| 3.10.1 | A Corrected Approach on the Wide-Beam ACD Method | 146 |
| 3.10.2 | The Effect of Vapor Condensation in the Bubble Size Estimation. | 148 |
| 3.11 | Summary | 148 |
| | References. | 149 |
| 4 | Cavitation-Enhanced Thermal Effects and Applications | 151 |
| 4.1 | Introduction | 151 |
| 4.2 | Principles of Cavitation-Enhanced Thermal Effects | 153 |
| 4.2.1 | Heating Due to Primary Absorption of an Ultrasound Field. | 153 |
| 4.2.2 | Viscous Damping of Cavitation Bubble | 153 |
| 4.2.3 | Acoustic Energy Radiation from a Cavitation Bubble. | 155 |
| 4.2.4 | Increased Local Acoustic Absorption by Cavitation Bubble. | 158 |
| 4.2.5 | Bioheat Transfer Equation | 159 |
| 4.3 | Simultaneously Measuring Cavitation Activity and Temperature Rise | 159 |
| 4.3.1 | Cavitation and Temperature Rise in Phantoms | 160 |
| 4.3.2 | Cavitation and Temperature Rise in Tissues | 161 |
| 4.4 | High-Intensity Focused Ultrasound Ablation. | 164 |
| 4.4.1 | In Vitro Methods of Evaluating Cavitation-Enhanced Thermal Effects | 165 |
| 4.4.2 | In Vivo Applications of Cavitation-Enhanced Thermal Effects | 171 |
| 4.4.3 | Preclinical Evaluation of Cavitation-Enhanced Thermal Effects | 177 |
| 4.5 | Thermal Effects of Flowing Microbubbles | 179 |
| 4.5.1 | Effects of Blood Flow on Heating. | 179 |
| 4.5.2 | Cavitation-Enhanced Heating by Flowing Microbubbles | 181 |
| 4.6 | Enhancing Acoustic Cavitation with Multi-frequency Ultrasound | 191 |
| 4.7 | Boiling Histotripsy | 196 |
| 4.8 | Microscale Cavitation Heating and Nanoscale Thermometry | 198 |
| 4.9 | Summary | 199 |
| | References. | 200 |

| | | |
|----------|--|------------|
| 5 | Cavitation-Enhanced Mechanical Effects and Applications | 207 |
| 5.1 | Introduction | 207 |
| 5.2 | Acoustic Microstreaming and Stress Field Created by Oscillating Bubble | 208 |
| 5.2.1 | Theoretical Calculation of Cavitation Microstreaming | 209 |
| 5.2.2 | Experimental Observation of Cavitation Microstreaming | 214 |
| 5.2.3 | Shear Stress Induced by Microstreaming | 219 |
| 5.3 | Jet Formation and Shock Wave Emission During Ultrasound-Induced Bubble Collapse | 222 |
| 5.3.1 | High-Speed Observation of Liquid Jets and Shock Wave Emission | 222 |
| 5.3.2 | Theoretical Modeling of Bubble Dynamics | 234 |
| 5.4 | Applications | 237 |
| 5.4.1 | Lithotripsy | 237 |
| 5.4.2 | Histotripsy | 242 |
| 5.4.3 | Sonothrombolysis | 245 |
| 5.4.4 | Vascular Applications | 249 |
| 5.4.5 | Ultrasound-Enhanced Delivery of Drugs and Genetic Materials | 253 |
| 5.5 | Summary | 258 |
| | References | 259 |
| 6 | Cavitation Control and Applications | 265 |
| 6.1 | Introduction | 265 |
| 6.2 | Effect of Temperature on Cavitation | 267 |
| 6.2.1 | Effect of the Liquid Temperature | 267 |
| 6.2.2 | Temperature Dependence of PSNE-Induced Cavitation | 271 |
| 6.3 | Effect of Pressure on Cavitation | 278 |
| 6.3.1 | Effect of Static Pressure | 278 |
| 6.3.2 | Effect of Overpressure on Cavitation Suppression | 280 |
| 6.4 | Effect of Frequency on Cavitation | 286 |
| 6.4.1 | Frequency Dependence of Ultrasonic Cavitation | 286 |
| 6.4.2 | Enhancement of Cavitation by Multiple Frequencies | 287 |
| 6.5 | Radiation Force-Constrained Cavitation | 290 |
| 6.6 | Cavitation-Controlled Tissue Histotripsy | 295 |
| 6.6.1 | The Principle | 295 |
| 6.6.2 | Effect of Pulse Length | 296 |
| 6.6.3 | Effect of Duty Cycle | 306 |
| 6.6.4 | Histotripsy Monitoring by Imaging Feedback | 309 |

| | | |
|----------|---|------------|
| 6.7 | Cavitation Dosage Control During Ablation | 310 |
| 6.7.1 | Effect of Cavitation on Ablation Process | 310 |
| 6.7.2 | Methods for Controlling Cavitation During Ablation. | 310 |
| 6.8 | Drug Delivery Controlled by Low-Intensity Focused Ultrasound | 319 |
| 6.8.1 | Composite Sequence and Focal Pattern of Low-Intensity Focused Ultrasound | 320 |
| 6.8.2 | Spatially Controlled Microbubble Destruction. | 322 |
| 6.8.3 | Temporally Controlled Microbubble Destruction | 323 |
| 6.9 | Summary | 326 |
| | References. | 327 |
| 7 | Cavitation Imaging in Tissues | 331 |
| 7.1 | Introduction | 331 |
| 7.2 | Active Cavitation Imaging | 333 |
| 7.2.1 | Conventional ACI and Differential Imaging Methods | 333 |
| 7.2.2 | Ultrafast ACI | 337 |
| 7.2.3 | Typical UACI Results for HIFU Therapy. | 343 |
| 7.3 | Second-Harmonic and Subharmonic Cavitation Imaging. . . . | 347 |
| 7.4 | Cavitation Imaging with the Bubble Wavelet Transform Technique. | 352 |
| 7.4.1 | CBWT Imaging Method | 353 |
| 7.4.2 | CBWT Imaging Method with the Pulse Inversion . . . | 357 |
| 7.5 | Bubble Doppler Technique for Cavitation Imaging | 358 |
| 7.6 | Passive Cavitation Imaging | 361 |
| 7.6.1 | Time-Domain PCI. | 361 |
| 7.6.2 | Fourier Domain PCI | 363 |
| 7.6.3 | Techniques for Improving the Resolution of PCI. . . . | 365 |
| 7.7 | Cavitation Imaging Based on Super-Resolution Reconstruction | 370 |
| 7.7.1 | Principles of Super-Resolution Reconstruction | 370 |
| 7.7.2 | POCS Reconstruction Approach | 372 |
| 7.8 | 3D Cavitation Imaging. | 376 |
| 7.8.1 | Brief Description. | 376 |
| 7.8.2 | 3D Ultrafast Cavitation Imaging Based on Adaptive Beamforming | 377 |
| 7.8.3 | Compressed Sensing and Sparse Modeling Method | 379 |
| 7.8.4 | Sparse Array Design | 384 |
| 7.9 | Magnetic Resonance Cavitation Imaging | 391 |
| 7.10 | Summary | 393 |
| | References. | 395 |

| | | |
|----------|--|------------|
| 8 | Laser-Induced Cavitation and Photoacoustic Cavitation | 401 |
| 8.1 | Introduction | 401 |
| 8.2 | Laser-Induced Cavitation | 402 |
| 8.2.1 | Brief Description. | 402 |
| 8.2.2 | LIC Modeling. | 405 |
| 8.2.3 | LIC in Water | 413 |
| 8.2.4 | LIC in a Phase-Shift Liquid | 419 |
| 8.2.5 | LIC of Droplets | 423 |
| 8.2.6 | LIC in a Cell | 424 |
| 8.2.7 | Plasmonic Nanoparticle-Generated Photothermal Bubbles | 425 |
| 8.3 | Photoacoustic Cavitation | 431 |
| 8.3.1 | Definition | 431 |
| 8.3.2 | PAC Modeling | 432 |
| 8.3.3 | Experimental System | 438 |
| 8.3.4 | PAC in Water. | 439 |
| 8.3.5 | PAC in a Phase-Shift Liquid | 440 |
| 8.3.6 | PAC of Nanodroplets | 442 |
| 8.3.7 | PAC with Nanoparticles. | 444 |
| 8.4 | Summary | 452 |
| | References. | 452 |
| 9 | Cavitation Mechanobiology and Applications | 457 |
| 9.1 | Introduction | 457 |
| 9.1.1 | Bioeffects of Ultrasound and Cavitation. | 457 |
| 9.1.2 | Cavitation Mechanobiology | 459 |
| 9.1.3 | Physical Mechanisms. | 461 |
| 9.1.4 | Chemical Mechanisms | 463 |
| 9.1.5 | Basic Applications | 464 |
| 9.2 | Mechanical Effects of Cavitation on Tissues. | 467 |
| 9.2.1 | Thrombolysis and Thrombolytic Therapy | 467 |
| 9.2.2 | Cavitation-Mediated Macromolecule Delivery. | 468 |
| 9.2.3 | Gene Therapy. | 469 |
| 9.2.4 | Anticancer Therapy | 472 |
| 9.2.5 | BBB and Neurodegenerative Disorder Therapy | 473 |
| 9.2.6 | Ultrasound Tissue Erosion and Histotripsy | 474 |
| 9.3 | Cavitation and Cells | 475 |
| 9.3.1 | Sonoporation | 475 |
| 9.3.2 | Cell Viability | 476 |
| 9.3.3 | Cell Death | 478 |
| 9.3.4 | Subcellular Effects | 482 |
| 9.3.5 | Molecular Mechanisms | 485 |
| 9.3.6 | Sonodynamic Therapy | 489 |

| | | |
|-------|--|-----|
| 9.4 | Effects of Cavitation on Macromolecules and Small Molecules | 491 |
| 9.4.1 | Effects of Cavitation on Small Molecules. | 492 |
| 9.4.2 | Effects of Cavitation on Macromolecules | 493 |
| 9.5 | Summary | 494 |
| | References. | 495 |

Cavitation in Biomedicine

Principles and Techniques

Wan, M.; Feng, Y.; Haar, G.t. (Eds.)

2015, XVII, 503 p. 403 illus., 104 illus. in color.,

Hardcover

ISBN: 978-94-017-7254-9