

Index

- absolute temperature 22, 58
- absorption 42, 189, 203, 217, 245
- acoustic cavitation 110, 115,
126–128
- acoustic cycle 128–130, 132–134
- acoustic wave 128
- adhesion 12, 157, 170, 180, 184,
185, 188, 221
- adsorption 180, 186, 218, 265
- advanced quick bonding implants
241
- aeration 255, 262, 267
- agent
 - anticancer 219, 249
 - antimicrobial 238
 - antiseptic 238, 239
 - bubble contrast 222
 - spin-trap 124
 - theranostic 221, 229
 - therapeutic 228
 - thrombolytic 217
- air bubbles 35, 172, 175, 262
- air flow 262, 263
- air-tight and constant temperature
storage (ATCT storage) 258,
261, 263, 264
- Alzheimer's disease 227
- ambient liquid pressure 110, 111,
117, 123, 137
- antibody 206, 208, 218, 221
- antimicrobial effect 237, 239, 243
- application 5–8, 10, 11, 13, 29,
30, 54, 56, 179, 180, 192,
199, 200, 203, 205, 216, 218,
220–222, 224
- biological 191
- chemical engineering 4
- clinical 202
- diagnostic 216
- environmental 11
- food hygiene 187
- systemic ozone 243
- therapeutic 216
- topical 248
- approach 183, 185, 186
 - chemotherapeutic 221
 - least-square 258
 - molecular dynamics 22
 - pharmaceutical 217
 - surgical 242
 - therapeutic 224
- aqueous ozone 201, 237, 239
- aqueous solution 41, 53, 54, 124,
141, 146
- argon 131, 132, 134, 135
- ATCT storage *see* air-tight and
constant temperature storage
- bacteria 222, 239–242
- barley seeds 9, 194, 196
- BBB *see* blood–brain barrier
- blood–brain barrier (BBB) 218,
227
- Boltzmann constant 22, 58, 118
- Boltzmann factor 115
- brain-derived neurotrophic factor
228
- Brownian motion 22, 56–59, 256,
257
- bubble collapse 127, 128, 131,
132, 134, 187, 204
- bubble concentration 172, 256,
258, 266
- bubble diameter 23–25, 28, 58, 60,
67, 81, 85

- bubble generation 39, 40, 45, 50, 51, 54, 55, 94, 104–106, 203
- bubble generator 3, 5, 11, 35, 49–53, 94, 97, 101, 255
- bubble growth 35, 40, 41, 44, 45
- bubble radius 110–114, 119, 123, 128–132, 134, 136, 138, 140
- bubble surface 12, 18, 26, 27, 115, 117, 119, 120, 124, 135, 171, 175, 266–268
- bubble wall 120–122, 129, 135, 137, 139, 140
- bulk water 73, 119, 254, 257, 266
- buoyancy 23, 34, 35, 135, 156, 186, 187

- cancer 201, 202, 205, 208, 219, 220, 226
 - human pancreatic 223
 - lung 201
 - malignant 226
 - non-prostate 226
 - ovarian 227
- carrot 195, 196, 198
- cavitation 6, 29, 36, 126, 127, 141, 147, 156, 157, 160, 202, 218
- cavitation nuclei 115, 116, 217
- cell 51, 52, 67, 68, 73, 192, 193, 195, 198–203, 206–208, 217, 219, 222, 243, 245
- brain parenchymal 228
- cancer 201, 202, 205–208, 218, 219, 223–226
- cultured 208
- endothelial 248
- human mesenchymal stem 249
- living 198, 199
- lung carcinoma 206
- ozone-activated immune 248
- cerebrospinal fluid 199
- chemotherapy 202, 208, 220, 223, 226
- Chlamydia trachomatis* 222
- cleaning effect 6, 9, 10, 13, 185, 187
- cleaning mechanism 185, 189, 190
- cleaning technology 179, 180
- coalescence 31, 38, 41, 187, 258
- coefficient
 - kinematic viscosity 160
 - mass transfer 41, 43
 - two-phase friction 24
- collision 22, 23, 30, 31, 38
- condition
 - acidic 147
 - air-tight 258, 261
 - equilibrium 11
 - experimental 129
 - healthy 197
 - hypoxic 201, 223
 - mass balance 123
 - normoxic 202
 - wettable 183
- contaminant 40, 184, 185
 - organic 4, 5
 - solid 95
- contamination 60, 92, 104, 158, 184, 255, 256
- Coulter method 62, 63
- crop growth 192, 197, 198
- cumulative interceptive supportive therapy 242
- cytoplasm 207, 218, 246
- cytosol 197, 205

- DDS *see* drug-delivery system
- degassed water 115, 123, 259
- detachment 53, 79, 185
- detection 4, 173, 204, 206–208, 221
- detector 89, 206
 - photodiode 172
- detergent 8, 18, 48, 179, 185
- device 4, 7, 13, 18, 28, 29, 36, 88, 227
- diagnosis 204, 205, 216, 217, 226, 229

- diffusion 22, 58, 60, 129, 267
- dirt 179, 180, 184
- disease 204, 216, 219, 225, 226, 229, 238
 - abdominal organ 216, 217
 - bacterial inflammatory 249
 - chronic 222
 - chronic inflammatory 238
 - difficult-to-cure 216
- dissolution 21, 23, 109–111, 113, 115–119, 129, 135–138, 140, 146, 187–189, 197
- DLS *see* dynamic light scattering
- doxorubicin 208, 220, 226
- drug 187, 207, 216–218, 220
 - anticancer 205, 208, 218
 - encapsulated 206, 207
 - tumor 220
- drug carrier 207, 217
- drug delivery 205, 217, 219, 227
 - noninvasive image-guided 220
 - sonoporation 218
- drug-delivery system (DDS) 217, 220, 221
- dynamic light scattering (DLS) 59, 60, 155, 156
- effect
 - antibacterial 238, 249
 - antioxidant 197
 - antitumor 202
 - lubrication 11
 - microbiological 240
 - negative 195
 - oxidative 197
 - pathological 195
 - synergistic 217, 222
- egg phosphatidylserine 74
- electric field 27, 67–69
- electrode 27, 62, 63, 67
- electrolyte solution 56, 63, 68, 200
- electron bombardment 76
- electron spin resonance (ESR) 124, 126, 141, 239
- electrophoresis 67, 68
- endosomes 205–208
- environment 21, 31, 156, 179, 204
 - cancer cell 202
 - hypoxic 201, 223
 - intestinal 200
 - vibration-free 255
- EPDM *see* ethylene propylene diene monomer
- epidermal growth factor receptor 206
- epithelization 248
- Epstein–Plesset theory 111, 113
- equilibrium 41, 43, 64, 111, 120, 122
- Escherichia coli* 222
- ESR *see* electron spin resonance
- ethylene propylene diene monomer (EPDM) 158, 159
- fiber 144, 146, 147
- film 76, 78, 257, 263, 266
 - collodion 76
 - polycarbonate 93
 - solid 18
 - wrinkled 77, 80, 83
- flow path 31, 32, 36, 51, 65, 66, 100, 173
- flow rate 29, 33, 49, 63, 67, 94, 101, 160
- fluorescence intensity 125, 126, 195
- flux 129, 130, 175, 176
- force 32, 34, 35, 58, 180, 181
 - capillary 33, 34
 - centrifugal 30
 - muscle 199
 - repulsive 113, 115
 - shearing 185
- fracturing 73, 75, 76, 78–80, 85
- equatorial 80, 85
- shallow 78, 85
- free energy 142, 180–182, 184–186

- freeze-thaw process 253, 259, 260, 267
- gas bubbles 115–117
- gas diffusion 113, 115, 117, 119, 122, 135, 263, 266
- gas dissolution 12, 41, 52, 122, 155, 159, 176
- gas-filled bubbles 253, 254, 259, 267
- gene delivery 224, 228
- genes 45, 196, 200–202, 218, 224, 225, 245, 246
- gene therapy 201, 208, 219, 224–226
- gene transfection 218, 224
- germination 9, 192, 195, 197
- Gibbs energy 122
- Helicobacter pylori* 200
- Henry's constant 120
- Henry's law 38, 39
- HIFU *see* high-intensity focused ultrasound
- high-intensity focused ultrasound (HIFU) 227, 228
- hydrodynamic cavitation 124–128, 255
- hydrophobic material 12, 110, 118–124, 135, 142–146, 176, 254
- hypoxia 201, 223
- ice grain boundaries 84, 85
- image
- echographic 216
 - freeze-fracture replica 76
 - high-contrast 85
 - higher resolution ultrasound 219
 - high-magnification 84
 - microscopic 73, 194
 - two-dimensional projection 77
- imaging 74, 216, 219, 220, 226
- diagnostic tumor 205
- magnetic resonance 227
- molecular 221, 227
- two-dimensional transmission 80
- ultrasound contrast 226
- implants 241–243
- infection 223, 247, 248
- inflammation 242, 246–248
- interfacial tension 28, 34, 49, 53, 181–185
- irradiation 54, 56, 174, 175, 191, 192, 207, 208, 226, 244
- irrigation 198, 238, 240, 242, 243
- ischemia 199, 221
- Knudsen number 138, 140
- Laplace equation 25
- Laplace pressure 110, 112–115, 117, 260
- large bubbles 32, 33, 42, 43, 47, 51, 187
- laser 56, 57, 59, 61, 62, 191, 202, 203, 206, 207
- lettuce 9, 89, 99, 104, 198
- lettuce factory 94, 99, 107
- liquid film 110, 142–147
- liquid flow 32, 33, 35, 36, 42, 49, 50, 66, 121, 122, 127, 159
- liquid phase 40, 41, 47, 180, 182, 184
- aerated 24
 - conductive 69
 - thin 170
- liquid water 47, 111, 115, 117, 118, 120, 122–124, 129, 132, 133, 137, 141–143, 146, 147
- low-level laser therapy 249
- MAPK *see* mitogen-activated protein kinase
- MAPK signaling pathway 245, 246
- MBs *see* microbubbles

- medicine 19, 215, 216, 218, 220, 222, 224, 226, 228, 229
- membrane 4, 47, 49, 53, 75, 80, 217, 222, 254
 - basement 248
 - flexible polyurethane 94
 - hollow fiber 256
 - porous 35
- membrane filter (MF) 6, 92, 99
- MEMS *see* microelectromechanical system
- metal 2, 64, 162, 254
- MF *see* membrane filter
- microbubble generation 28, 33, 35, 43, 47–49
- microbubble generator 18, 27, 29–33, 35, 36, 38, 42, 43, 45, 48, 50, 156
- microbubbles (MB) 1–4, 7, 8, 11–13, 17–38, 42–52, 60, 61, 69, 73–83, 85, 116, 117, 123, 124, 186, 187, 189, 215–219, 224, 226, 227
- microelectromechanical system (MEMS) 65, 67, 170
- micropores 34–36, 53
- Mie scattering theory 60
- mitogen-activated protein kinase (MAPK) 237, 243–245
- model 94, 100, 113, 115–117, 121, 122, 135, 156, 157, 176, 208, 254
 - 3D tissue 102
 - armored bubble 116, 117
 - box 119
 - continuum 137
 - corneal epithelium 100
 - dynamic equilibrium 12, 13, 109, 110, 113, 118, 121–124, 142, 146, 157, 175, 176, 254, 265, 266
 - electrostatic repulsion 113
 - equilibrium 123
 - human skin 100
 - mouse 247
 - mouse xenograft-tumor 223
 - rabbit 199, 222
 - rat calvarial defect 243
 - skin 115, 116, 123, 157, 176
 - skin regeneration 100
 - theoretical 129, 135
- nanobubbles 2, 19, 125, 126, 192, 202, 228, 239, 259
- nanoparticles 117, 203, 206, 208, 228, 259
 - metal 202, 203
 - plasmonic 192, 203
- nanoparticle tracking analysis (NTA) 56, 88, 93, 256
- nanopores (NPs) 93, 94, 100, 203, 204
- NC *see* negative control
- negative control (NC) 102, 103, 244
- net number concentration (NNC) 264–266
- nitrogen 38, 39, 43, 44, 46–48, 132
- NNC *see* net number concentration
- nozzle 42, 43, 45, 47, 49, 50, 124, 158, 160, 161, 255, 262
- NPs *see* nanopores
- NTA *see* nanoparticle tracking analysis
- numerical simulations 128–137, 140
- nylon 257, 263, 265, 266
- organ 216, 217, 219, 225, 228
- organic material 12, 115, 116, 155, 162, 164, 165, 169, 170, 173, 175, 176
- organism 191–193, 197–201
- OUFBW *see* ozone ultrafine bubble water
- oxidant 127, 128, 132, 135, 197
- oxidative stress 200, 237, 238, 243–246, 249

- oxygen 3, 38, 39, 43, 44, 48, 125, 127, 136, 137, 140, 192–194, 197–199, 201, 209, 237, 239
- oyster 3, 18, 29
- ozone 102–104, 192, 200, 201, 237, 239, 243, 244, 247–249
- ozone ultrafine bubble water (OUFBW) 87, 89, 100, 101, 103, 104, 200, 201, 237–249

- particle tracking analysis (PTA) 56–58, 60, 88, 93, 256, 262
- patient 201, 222, 224, 238, 241, 242, 249
- peri-implantitis 237, 241–243
- periodontitis 200, 237–240, 243, 249
- periodontopathic bacteria 239, 242
- phospholipids 216, 217, 224
- plasmonic nanobubbles (PNBs) 191, 192, 202–209
- plasmonic nanoparticles (PNPs) 203, 204
- PNBs *see* plasmonic nanobubbles
- PNPs *see* plasmonic nanoparticles
- polymer material 254, 255, 264, 265, 267
- pressure 25, 26, 28, 30, 38–44, 46, 48–50, 110–115, 120, 126, 127, 137, 139, 140, 159, 160
 - absolute 160
 - acoustic 128, 220
 - ambient 111
 - atmospheric 6, 26, 30, 39, 41, 49, 74
 - focal 227
 - negative 41, 114
 - partial 39, 47, 198
- pressure amplitude 115, 128, 130
- protein 69, 193, 200, 216, 217, 243, 246
- Pseudomonas aeruginosa* 222

- PTA *see* particle tracking analysis
- pump 29–31, 41–43, 47, 92, 157–161, 257
 - integrated syringe 256
 - peristaltic 92
 - submersible 30
 - vacuum 62, 63, 100
- pure water 22, 54, 76, 110, 113, 126, 141, 253, 255, 256, 267
- Pythagorean theorem 57

- qNano 87–89, 93–97, 99, 104–107, 243
- quick-freeze replica technique 64, 65, 73–75, 77–79, 81–83

- radiation 205, 207
 - hypoxia-induced 201
 - optical 204
- radiation therapy 201, 224
- radicals 109, 110, 124–130, 137, 141, 147
 - free 239
 - reactive 193
- Rayleigh collapse 127, 129
- reaction 10, 137, 141, 147
 - chemical 11, 48, 109, 110, 127, 129, 147, 180
 - dismutation 194
 - slow 141
 - sonochemical 127
- reactive oxygen species (ROS) 45, 192–195, 197, 200, 201, 209, 237, 243–246, 248
- replica membrane 73, 74, 78–81, 84, 85
- resistance 201, 202, 223
 - electrical 56, 62, 63
 - hypoxia-induced 224
 - microbial 237, 239
- Reynolds number 22, 160
- ROS *see* reactive oxygen species
- rupture 20, 143, 144, 146, 147

- sample 59, 60, 62, 64–67, 74–76, 89, 90, 92–94, 99, 100, 105–107, 169, 172, 253, 256, 257, 259, 260
- aqueous 259
- biological 73
- bubble 74
- dirt model 188
- freezing 74
- frozen 64, 74, 76, 79, 84
- hydrous 73
- non-biological 73
- polymer 264
- standard 95
- test 81, 86
- SBSL *see* single-bubble sonoluminescence
- scattered light 56–59, 61, 62, 104, 203, 204
- scattering method 60–62, 155, 156
- Schwann cells 248
- seed germination 9, 194, 195, 197, 254
- shrinkage 21, 26, 27, 36, 157
- shrinking phenomena 7, 13
- signal 124–126, 141, 203, 206
- single-bubble sonoluminescence (SBSL) 128–132, 135
- sonoluminescence 128
- species 135, 192
 - chemical 132, 133, 181
 - non-reactive 132
 - reactive oxidizing 239
 - soluble 132
- spinach seeds 195, 196
- spinal cord ischemic injury 199
- spinal neurons 199
- sprout growth 192, 195
- Staphylococcus aureus* 223
- Stokes–Einstein equation 22, 23, 27, 58, 60, 256
- storage 253, 255, 257–259, 261, 263, 265, 267
- storage conditions 104, 254, 263
- surface nanobubbles 121, 122
- surface tension 6, 110, 114, 116, 137, 141–147, 181–184
- surfactant 2, 3, 28, 48, 53, 54, 115–117, 141, 142, 144–146, 179, 226
 - anionic 141, 144
 - cationic 142, 145
 - nonionic 142
- system 33, 45, 47, 52, 94, 104, 122, 255
 - bubble-producing 52
 - data-handling 89
 - experimental 160, 169
 - flow culture 99, 100
 - immune 222, 224
 - intravascular 216
 - irrigating 100, 104
 - isolated 55
 - nanoparticle Brownian motion tracking 59
 - power plant cooling seawater 8
 - pressurized 39
 - quality-controlled monitoring 228
 - single-bubble 128
 - single-pass 30
 - streptavidin 226
 - ultrapure water production 3, 4
- Tannerella forsythia* 238
- temporal change 63, 254, 255, 263, 264, 266, 267
- temporal variation 253, 254, 258–260, 264, 265
- theranostics 204, 205, 208, 209, 220
- therapy 192, 219, 224, 226, 227, 229, 237, 241
 - adjunctive 249
 - antibiotic 242
 - low-level laser 249
 - periodontal 238, 239

- surgical 242
- thermal ultrasound 227
- tumor 228
- tumor-selective 201
- tissue 73, 198, 199, 207, 216, 217, 220, 224
 - granulation 247
 - human oral 239
 - malignant 219
 - periodontal 246
 - prostate 226
 - spinal cord 199
- TOC *see* total organic carbon
- total organic carbon (TOC) 101, 162, 164, 165, 176
- toxicity 205, 206, 208
- transmission electron microscopy 12, 73, 74, 76, 78, 80, 82, 84, 86, 155, 254
- treatment 10, 199–201, 204, 205, 207, 208, 218, 238, 240–242, 244, 249
 - acute spinal cord injury 228
 - anticancer 199
 - nonsurgical 241
 - oral hygiene 242
 - peri-implantitis 242
 - single pulse 205
 - slow freezing 65
 - topical 223
 - wastewater 19, 254
- Treponema denticola* 238
- tumor 201, 223, 228
 - malignant 201, 216, 219, 221, 223
- tunable resistive pulse sensing 88
- UBM *see* UFB monitor
- UBM apparatus 90, 91, 93, 104
- UFB concentration 156, 159–170, 172, 174, 175, 255, 265
- UFB dispersion 81, 82, 86, 253, 267
- UFB generation 161, 162, 167, 168, 255, 257
- UFB monitor (UBM) 87–92, 101, 102
- UFBs *see* ultrafine bubbles
- UFB water 89, 91–94, 96, 97, 99, 104–107, 157, 159, 162–164, 166, 192–198, 200, 209, 257, 261–265, 267
- ultrafine bubbles (UFBs) 1–13, 19–23, 48–57, 59–61, 63–67, 81–85, 87–89, 92–95, 109–114, 122–126, 140–147, 155, 156, 164–166, 168–170, 174–176, 187, 189–202, 218–229, 253–262, 266–268
- ultrapure water (UPW) 1, 4–7, 13, 52, 89–92, 157, 158, 161–164, 169, 170
- ultrasonic irradiation 54, 174, 175, 225, 259
- ultrasonic waves 35, 54, 130, 174, 208
- ultrasound 54, 115, 116, 126, 128, 135, 137, 207, 217, 218, 220–222, 227, 228
 - compression phase of 126, 129
 - diagnostic 220
 - rarefaction phase of 126, 129
 - surfactant type 49
- ultrasound contrast agent 215–217, 219, 226
- ultrasound irradiation 128, 218, 221, 222, 224
- UPW *see* ultrapure water
- vapor 39, 41, 43, 44, 47, 120, 127, 129, 180, 204
 - water 47, 127, 129, 134, 137, 257, 266
- vascular endothelial growth factor 248
- Venturi tube 37, 38, 127, 156

- Venturi type microbubble
 - generators 37, 38
- violent collapse 127, 128, 132, 137
- washing machine 11, 185
- water 6, 8–12, 20–23, 25–31,
 - 38–54, 74–76, 81–83, 85,
 - 87–90, 92, 109–111, 118–122,
 - 124, 125, 128–130, 156, 157,
 - 175, 176, 186, 187, 189, 190,
 - 193–202, 240, 241
- aerated 198
- agricultural 50
- air-saturated 115
- bottled 99
- clean 21
- cloudy 52
- distilled 5, 27, 194–196
- drinking 239
- gas-saturated 45, 111
- microbubbles-included 3
- nanobubble 198
- ozone nanobubble 239–241
- supersaturated 39, 40, 45
- transparent 156
- ultrafine-bubbles-contained 12
- unfrozen 65
- washing 8, 187
- wound healing 238, 246–249

"This is the first outstanding book focusing on the comprehensive features of ultrafine bubbles (UFBs). It covers their versatile aspects such as history, fundamentals, and latest applications, and in particular, their existence, stability, and radical formations. It is strongly recommended not only for researchers but also beginners interested in UFBs and wishing to gain new knowledge on the emerging UFB science and technology."

Prof. Emer. Kiyoshi Yoshikawa
Kyoto University, Japan

"This book is the bible of UFB research, discussing the characteristics, generation methods, and industrial applications of UFBs, as well as mechanisms of their various effects."

Prof. Takashi Hata
National Institute of Technology, Kochi College, Japan

UFBs are gas-filled bubbles having a diameter smaller than 1 μm . They are sometimes called bulk nanobubbles because these are not on a solid surface but inside a bulk liquid (water). They are already being used in commercial processes such as cleaning and plant cultivation. However, many mysteries still exist with respect to UFBs, such as mechanisms of stability, OH radical formation, and biological and medical effects. This is the first book on UFBs that reviews researches done on them. It is helpful for students and researchers interested in the fundamentals of this emerging field and its applications, including cleaning, biological, medical, and dental ones.



Koichi Terasaka is a professor at the Department of Applied Chemistry, Keio University, Japan. He is also chair of the Union of Fine Bubble Scientists and Engineers, director of the Fine Bubble Industries Association, and expert of ISO/TC 281 (fine bubble technology) committee. He is a chemical engineer who has been involved with bubble engineering since the 1980s and has recently been working on industrial application of UFBs.



Kyuichi Yasui is a senior research scientist at the National Institute of Advanced Industrial Science and Technology (AIST), Japan. He received his PhD from the Department of Physics, Waseda University, Japan, in 1996. His current research focuses on numerical simulations on UFBs and other topics in sonochemistry, sonoluminescence, acoustic cavitation, and nanocrystals.



Wataru Kanematsu is a former principal research manager at AIST. He is involved in research on characterization of UFBs and UFB-containing liquid. Industrial standardization of characterization technology is another technical interest for him.



Nobuhiro Aya is a supervisory innovation coordinator at AIST. His scientific interests are focused mainly on fine bubbles and fine particles and also on methodological issues on combination and integration of various technologies and improvement of industrial/social usage of technologies. He is also the committee manager of the ISO/TC 281 (fine bubble technology) since its establishment in 2013.



JENNY STANFORD
PUBLISHING

V817
ISBN 978-981-4877-59-6



9 789814 877596