

Index

a

- abrasion resistance, particle strength 281
- active transponders, in primary-drying monitoring 98
- additives, enzyme stabilization 275
- ADH. *see* alcohol dehydrogenase
- adhesion
 - low molecular weight 239
 - mechanisms 299–315
 - powders 260–261
- adhesion bridges 299
- adhesion force, spray fluidized beds 296, 302–305
- adsorption
 - nitrogen 166–168
 - stress 270–271
- aerogels
 - SAXS spectra 164
 - supercritically dried 159
 - vacuum drying 198
- aged gels, shrinkage 200
- agglomerates
 - adhesion mechanisms and mechanical strength 299–315
 - breakage 314, 315–321
 - material structure 300–301
 - mechanical properties 312
 - mechanical strength 299–315, 308–315
 - preparation scheme 310
- agglomeration
 - dextrose sirup 307
 - discrete modeling 363–372
 - glass particles 370
 - particle formulation 296
 - particles properties 298
 - primary particle properties 321–324
 - spray fluidized bed processes 297
 - stochastic discrete modeling 363–372
 - tensile strength 308–310
 - triggering 370
- aging
 - cracks 199–201
 - effects on shrinkage 209
 - RF gels 208–209
 - shrinkage 200
- agricultural products, textured by drying 3
- alcohol dehydrogenase (ADH), activity retention 274–277
- alcohol dehydrogenase (ADH) powder, outer surface morphology 248
- alumina carrier particles 331
- alumina gels
 - crack patterns 175
 - diffusion models 213
- alumina monoliths 201
- amorphous glass state 261
 - vibrational motions 261
- amorphous particles
 - surface tension 305
 - viscous forces in sinter bridges 304–308
 - volume diffusion 305
- amorphous water-soluble materials 302
- anhydrous sugars, glass transition temperature 13
- annealing, influence on ice morphology 67–69
- anthocyanins, changes in drying process 7
- apparatus design, influence on product quality 332–338
- aroma compounds, retention of 9–10
- aromatic oils, spray fluidized bed encapsulation 358
- artificial neural network 359
- ascorbic acid, as a quality index in drying process 6
- attrition, particles strength 281–282

b

balances, for freeze-dryers 104–105
 band dryer, food industry 2
 barometric temperature measurement (BTM)
 – primary-drying monitoring 115
 – shelf-temperature control 128–129
 BaSO₄-suspension 243
 batch granulation
 – dispersive growth 344–349
 – dispersive growth in 344–349
 – growth 344–349
 batch monitoring
 – endpoint detection of primary drying 106–113
 – freeze-drying 106–125
 – using sublimation-flux measurement 113–114
 bed material, number density
 distribution 326
 belt dryer, food industry 2
 binder content, sprayed solution 325–326
 biochemical reactions, induced by drying 5–9
 bovine serum albumin (BSA)
 – primary-drying process 127
 – spray-dried particle morphology 250
 breakage behavior
 – agglomerates 315–321
 – cylindrical agglomerates 314
 – elastic-brittle 316–317
 – elastic-plastic 317–318
 – granules with layered structure 320–321
 – plastic 318–320
 breakage probability
 – binder contents 314
 – γ -Al₂O₃ agglomerates 315
 – granulation time dependence 325
 – retention effect 327
 breakage ratios, comparison of visual inspection and image analysis 32
 bridges
 – adhesion 299
 – liquid 303–304
 – sinter 304–308
 brown rice, obtainment of 22
 browning reaction, in drying process 8
 BSA. *see* bovine serum albumin
 BTM. *see* barometric temperature measurement
 buckling pressure, suspensions 242
 bulk modulus, drying methods 176

c

calorimetric measurements, single-vial monitoring 101

capillary forces
 – adhesion 299
 – liquid bridges between particles 303–304
 – pore sizes 167
 capillary pressure 175, 304
 capsule wall materials 257
 caramelization, in drying process 8
 carbohydrate polymers, glass transition temperature 13
 carbon aerogels, dry gels 161
 carbon cryogels, quality preservation 192
 cargo rice, obtainment of 22
 carotenoids, changes in drying process 6–7
 carrier materials, particle creation 247–251
 carrier matrices collapse 268
 carrier particles, loading with catalytic active components 329
 CCD camera, fissure formation in rice 28–29
 centrifugal rotary disk atomizer, spray drying 231
 CFD. *see* computational fluid dynamics
 chamber pressure. *see also* sublimation chamber
 – calculated by CFD 140–142
 – primary-drying control 93, 125–135
 chamber temperature. *see also* temperature
 – vial batch monitoring 118
 cherenkov detectors 161
 chlorophylls, changes in drying process 6
 chromatography 161
 Clausius-Clapeyron equation, low molecular weight substances 236
 CLSM. *see* confocal laser scanning microscopy
 CO₂, low-temperature gel drying 187–189
 coating 296–297
 cold chamber optical microscopy, freeze-drying 55–57
 cold plasma ionization, vial batch monitoring 110–111
 collapse temperature, freeze-drying 54–55
 colloidal gel networks 157
 color, as a quality index in drying process 6
 complex dispersions 244–251
 compression tests 310–311
 computational fluid dynamics (CFD)
 – calculation of local moisture content 12
 – design parameters 139–142
 confocal laser scanning microscopy (CLSM) 234, 247
 constant rate period (CRP) 236
 consumer products, gained by drying 3–4

contact stiffness 312
 continuous freeze-drying 142–143
 continuously operated stirred tank reactors (CSTR) 339
 control algorithms, primary freeze drying 125–135
 controlled nucleation
 – and physical quality 70–73
 – by ultrasound sonication 70–72
 convective drying
 – advanced modeling 211–220
 – contact angle 199
 – diffusion model 211–217
 – gels 174–182
 – hydrogel 175
 – quality preservation 198–210
 – RF gels 206
 convective hot air drying, and mechanical transformations 15
 cooling rate. *see* freezing rate
 – influence on dried layer permeability 66
 crack formation. *see also* fissured rice
 – convective gel drying 174–175, 180–182
 – critical drying rate 214
 – density change 183
 – during drying 16
 – initiation 181
 – in rice 26–27
 – shells 320
 – supercritical drying 188
 – surface and internal 25
 crack-free monoliths 190
 crack patterns 175
 crack propagation 316
 cracking, video acquisition 29
 cracks. *see also* fissured rice
 – from aging 199–201
 – surface and internal 25
 critical drying rate, crack formation 214
 cross-sectional structures, spray-dried powders 248
 CRP. *see* constant rate period
 crust formation, during annealing process 69
 cryogel flakes 191
 cryogels 159
 crystal nucleation. *see* nucleation
 crystalline substances, water-soluble 304
 crystallization
 – in drying process 10
 – low molecular weight substances 238
 – during storage 16–17
 CSTR. *see* continuously operated stirred tank reactors

d

D-limonene
 – flavor solubility 259
 – oxidation reaction 267
 – release kinetics 264
 – retention 258
 Darcy's law
 – differential shrinkage 177
 – freeze-dried layer permeability 76
 – PRT 60
 deep bed dryer, food industry 2
 dehydration stress 271–272
 depressurization, supercritical drying 186
 dewatering. *see also* drying
 dextrose sirup, fluidized bed agglomeration 307
 diametral compression test, rice grains 37
 dielectric measurements, single-vial monitoring 100–101
 differential scanning calorimetry (DSC)
 – freeze-drying 55
 – gel drying 164
 differential shrinkage
 – diffusion equation 178
 – and stress 177–180
 dihedral dryer, food industry 2
 discrete particle modeling (DPM)
 – agglomeration 363–372
 – principles 350–351
 – simulation parameters 351–352
 – Wurster coater 349–357
 distributor plates, apparatus design 337
 DPE. *see* dynamic parameters estimation
 DPM. *see* discrete particle modeling; drying process monitoring
 dried layer. *see* freeze-dried layer
 dried particles
 – lipids oxidation 279–280
 – porosity 280–281
 dried powder
 – flavor release 262–267
 – stickiness 260–261
 droplet drying 273–274
 droplet shrinkage 232
 droplet size, feed emulsion 258
 drugs. *see* pharmaceuticals
 drum dryer, food industry 2
 dry coating process 298
 dry gels
 – applications 160–162
 – catalysis 161
 – characterization 166–172, 166–174
 – conductivity 159
 – density 159

- dielectric constant 160
- elastic behavior 160
- hydrophobicity 160
- insulation 160
- optical coatings 161
- optical transparency 159
- other methods 171–172
- properties 158–160
- refractive index 160
- sound insulation 161
- sound speed 160
- surface area 159
- thermal conductivity 159
- thermal insulation 160
- transparency 159
- water treatment 161
- drying. *see also* dewatering; freeze-drying; gel drying
 - advanced modeling 211–220
 - convective 174–182, 198–210
 - encapsulation and microencapsulation of enzymes and oil by 269–280
 - gel characterization 172–174
 - gels 155–230
 - microencapsulation 269–270
 - microwave 210–211
 - oil emulsions 278–279
 - particle creation 251–253
 - preserving quality 189–211
 - process variables effect on the stabilization of enzymes 275–278
 - protein encapsulation theory 272–273
 - protein solutions 273
 - quality loss 174–189
 - retention of emulsified hydrophobic flavors 257–260
 - single suspended droplet 273–274
 - stress on proteins 270–272
 - subcritical 189–190
 - vacuum 197–198
- drying chamber. *see also* sublimation chamber
 - fluid dynamics in 139–142
 - water vapor pressure 62
- drying equipment, food industry 2
- drying modes
 - combined 17–18
 - in foods 14
- drying process
 - as a controlled texturing operation 3
 - impact on mechanical properties and crack formation in rice 21–45
 - quality changes in food materials 1–18
- drying process monitoring (DPM), single vials 101
- drying process severity, and food quality 5
- Drying3000 simulator 39
- DSC. *see* differential scanning calorimetry
- dynamic parameters estimation (DPE)
 - algorithm
 - primary-drying control 129, 132
 - vial batch monitoring 115–116
- e**
- easy-to-use products, gained by drying 3
- ebullition, as drying mode 14
- effective contact stiffness 312
- elastic-brittle breakage behavior 316–317
- elastic-plastic breakage behavior 317–318
- elastoplastic material, stress-strain relationship 36
- empirical curve fitting, modeling of rice quality 39
- emulsified hydrophobic flavors
 - retention 257–260
 - spray drying 256–257
- emulsions
 - complex dispersions 244–251
 - drop size 258
 - microencapsulated flavor powders 245–247
 - spray drying 278–279
- encapsulated flavor
 - glass temperature influence 261–262
 - oxidation 267
 - release and oxidation during storage 261–269
- encapsulated flavor droplets, CLSM pictures 246–247
- encapsulated lipids, oxidation 279–280
- encapsulation
 - enzymes and oil 269–280
 - neural networks 357–363
- endpoint detection, vial batch monitoring 106–113, 121–122
- enzymatic activity, and water activity 8
- enzyme activity retention 275
- enzyme stabilization
 - effect of process variables 275–278
 - effects of formulation composition 274–275
- enzymes
 - encapsulation and microencapsulation 269–280
 - particle creation 247–251
 - spray drying microencapsulation 269–270
 - thermal stress 271–272
- ethanol retention 256
- ethyl-*n*-butyrate powder

- flavor powders 246
- flavor release 262
- flavor solubility 259
- explosion puffing, combined with drying 18
- extended Kalman filter, single-vial monitoring 102
- f**
- failure strength, rice grains 36–39
- feed liquid, spray drying 231
- feedback controlling, primary-drying 134–135
- filling height, freeze-drying 66–67
- film thinning effect, low molecular weight substances 238
- fine glass filament suspension 272
- finite element modeling, modeling of rice quality 39
- finite strain tensor 218
- fish oil, oxidation kinetics 264
- fissure formation
 - characterization by image analysis techniques 28–33
 - count algorithm 31
 - segmentation method for characterization 30–31
- fissure ratios, comparison of visual inspection and image analysis 33
- fissured rice
 - definition 23–24
 - and relative humidity 24–28
- flash spray drying, suspensions 242
- flavor compounds, retention of 9–10
- flavor droplets, encapsulated 247
- flavor encapsulation, theory and mechanism 255
- flavor powders, microencapsulated 245–247
- flavor release
 - analysis by PTR-MS 266
 - humidities and temperatures 264, 266
 - mathematical modeling 262
 - and oxidation 261–269
- flavor retention, spray-dried food products 253–269
- flavor solubility 259
- flavor solution, spray-drying scheme 257
- flavors
 - emulsified 257–260
 - glass temperature influence 261–262
 - microencapsulation 254–256
 - oxidation 267
 - spray drying 256–257
- flaxseed, water activity effect 279
- fluorescein sodium salt, protein particles 248
- fluid dynamics, as quality parameter 139–142
- fluid temperature, primary-drying control 130
- fluidized bed agglomeration, dextrose sirup 307
- fluidized bed coating, process conditions 346
- fluidized bed dryer, food industry 2
- fluidized beds
 - catalyst impregnation 329–332
 - particle formulation 253, 295–378
- food industry, drying equipment 2
- food materials
 - biochemical reactions induced by drying 5–9
 - drying-process-influenced quality changes in 1–18
 - mechanical transformations induced by drying 14–16
 - physical transformations during drying 9–14
 - storage and rehydration of 16–17
- food particle bridges, capillary forces 303–304
- food particles
 - relaxation 302
 - viscoelastic deformation 302
 - viscous forces in sinter bridges 304–308
- food products
 - flavor retention 253–269
 - spray-dried 233
- food quality also quality
 - and drying process severity 5
 - gained by drying 4
 - and nutritional and sensory properties 4
- formulation. *see also* liquid formulation; particle formulation
 - complex dispersions 244–251
 - enzyme stabilization 274–275
- fractal drying front, crack formation 182
- fracture morphology, dry gels 160
- fracture surface
 - γ - Al_2O_3 agglomerates 316–317
 - sodium benzoate granules 321
 - zeolite agglomerate 319
- freeze-dried cake morphology
 - and physical quality 74–78
 - and water vapor mass transfer resistance 74–76
- freeze-dried cake permeability
 - PRT 59–61
 - theoretical 77
- freeze-dried layer permeability
 - experimental 77
 - influence of cooling rate 66
 - and water vapor mass transfer resistance 76–78

- freeze-dried matrix, moisture gradients in 52
 - freeze-dryer, food industry 2
 - freeze-dryer balances 104–105
 - freeze-drying. *see also* drying; primary-drying control; primary-drying monitoring
 - chamber pressure 93
 - cold chamber optical microscopy 55–57
 - collapse temperature 54–55
 - continuous 142–143
 - control of freezing step 94–96
 - control of primary drying 125–135
 - DSC 55
 - estimation of mean product temperature 61–63
 - gels 182–185
 - and glass transition 11
 - heat flux heterogeneity 57–59
 - ice structure and morphology 55–57
 - in-line product quality control 91–144
 - key quality factors 52–63
 - and mechanical transformations 14
 - melting curves 54–55
 - monitoring and control of secondary drying 135–138
 - MTM 59
 - of pharmaceuticals 51–86
 - PRA 59–61
 - principal basic phenomena 51–52
 - product quality during drying and storage 83–85
 - product-temperature maintenance 91
 - quality parameters 139–142
 - quality preservation 190
 - residual water content 91–92
 - RF and carbon cryogels 192–193
 - shelf temperature 93
 - state diagram 54–55
 - vitreous transition 54–55
 - freeze-drying microscopy 55
 - freeze-drying parameters, influence on physical quality factors 63–82
 - freeze-drying process, different steps 52, 91
 - freeze spray drying, particle creation 251–253
 - freezing process, and tensile stress 184
 - freezing protocol, influence on ice morphology 63–69
 - freezing rate, influence on ice morphology 55–56, 64–66
 - freezing step. *see also* nucleation
 - control of 94–96
 - full milk particle, agglomerated 253
 - functional oils 278
 - functionalities, of food materials 1
- g**
- γ -Al₂O₃ agglomerates
 - breakage probability 315
 - fracture surface 316–317
 - γ -Al₂O₃ particles
 - elastic-brittle breakage behavior 316
 - used to produce agglomerates 310
 - gap distance, Wurster coater 355–357
 - gas distributor, apparatus design 333
 - gas recycling, apparatus design 332
 - gas temperature, in chamber. *see* chamber temperature; temperature
 - Gaussian blobs 322
 - gel applications, quality aspects 156–162
 - gel drying 155–230
 - cracking 180–182
 - differential shrinkage 176–180
 - freezing 182–185
 - low-temperature process 187–189
 - methods 174–189
 - phase diagram 174
 - supercritical 159, 185–189
 - X-ray tomography 172
 - gel networks 157
 - gel structure
 - changes 155–230
 - characterization 162
 - destruction 183
 - during drying 155
 - resorcinol-formaldehyde gels 158
 - gel synthesis, optimization 194
 - gelatinization 245
 - gelation
 - quality aspects 156
 - ultrasonic irradiation 195
 - gelinization, starch 245
 - gels
 - aging 208–209
 - applications 160–162
 - characterization during drying 172–174
 - characterization of dry 166–172
 - characterization of wet 162–166
 - crack patterns 175
 - diffusion models 213
 - ice templating 195–197
 - polymer crosslinking 201
 - preparation 156–157
 - properties 158–160
 - quality aspects 156–162
 - resorcinol-formaldehyde 157–158, 204–208
 - RF aging 208–209
 - RF convective drying 206
 - RF freeze drying 191
 - RF linear shrinkage 209

- RF quality preservation 204–208
- RF SAXS spectra 164
- RF synthesis 157–158
- shrinkage 200
- shrinkage prevention and cracks
 - by aging 199–201
- shrinkage reversion 201–204
- silica 156–157
- structural characterization 162
- technical 158
- transmission electron microscopy 171
- wet 156–158
- glass encapsulation 254
- glass particles
 - agglomeration 370
 - growth 368
- glass transition curve, in drying
 - process 10–11
- glass transition temperature
 - of anhydrous sugars and carbohydrate polymers 13
 - low molecular weight substances 238
 - relaxation process correlation 267–269
 - spray-dried powder stickiness 260
 - and storage stability of encapsulated flavor 261–262
- glassy particles
 - lactose 238
 - surface of 261
- Gordon-Taylor constant 300
- grains, rice. *see* rice grains
- granulated particles, mechanical
 - strength 324–329
- granulated products, breakage 315–321
- granulation
 - dispersive growth 344–349
 - particle formulation 296
 - particles properties 298
 - spray fluidized bed processes 297
- granulator, radial particle distribution 353
- granule shapes 327
- granules, breakage behavior 320–321
- gray level histograms, rice grains 29
- growth rates
 - low molecular weight substances 238
 - total 346
- Guidance for Industry PAT (Process Analytical Technology) 92, 143
- Guinier regime 163

h

- hard shell particles 244–245
- head rice yield (HRY)
 - definition 23

- kinetics 43–44
- heat flux heterogeneity, freeze-drying 57–59
- heat transfer coefficient, for tubing
 - vials 58–59
- hexamethyldisiloxane (HMDSO) 203
- hierarchical pore collapse 169
- high gain observers, single-vial
 - monitoring 102
- high-porosity particles, morphology 235
- highly hydrated agricultural products, textured
 - by drying 3
- highly insulating and light transmitting
 - (HILIT) aerogel 189
- HMDSO. *see* hexamethyldisiloxane
- hollow particles
 - morphology 235
 - outlet temperature 251, 252
 - SBS-latex 241
- Hooke's law, rice grains 34
- horizontal fluidized bed unit 337
- hot air drying
 - freeze drying replacement 195
 - RF and carbon cryogels 192
- hot melt coating 299
- HRY. *see* head rice yield
- human recombinant interferon, ultrasound
 - triggered nucleation 96–97
- hybrid gels 204
- hydrogels
 - convective drying 175
 - vacuum drying 197
- hydrolysis, silica gelation 156
- hydrophilic flavors,
 - microencapsulation 255–256
- hydrophobic flavors
 - retention of emulsified 257–260
 - spray drying 256–257
- hydrophobic silica xerogel 203
- hydrophobicity, dry gels 160
- hygrocapacity, material structure 300
- hygroinsensitivity 300

i

- ice crystal size, distribution of 65, 67–68
- ice crystal structure
 - observation methods 57
 - on vertical cross-sections 73
- ice fog method, controlled nucleation 70
- ice morphology
 - influence by annealing 67–69
 - influence by freezing protocol 63–69
 - influence by freezing rate 55–56, 64–66
 - influence by supercooling 55, 63

- influence by vial type and filling height 66–67
- and physical quality factors 63–69
- ice penetration, pores 165
- ice structure, freeze-drying material 55–57
- ice sublimation front temperature 62
- ice templating 195–197
- ICP-AES. *see* inductively coupled plasma/atomic emission spectroscopy
- image analysis techniques
 - compared to visual inspection 32–33
 - fissure formation in rice 28–33
- IMC. *see* internal model control
- impregnation, catalyst 329–332
- in-line product quality control, pharmaceuticals 91–144
- inductively coupled plasma/atomic emission (ICP-AES) spectroscopy, vial batch monitoring 110–111
- industrial products, textured by drying 3
- integral square error (ISE), primary-drying control 131, 134
- integrated fluidized beds, particle creation 253
- intermediate industrial products, textured by drying 3
- internal cracks, rice 25
- internal model control (IMC), primary-drying control 133
- ISE. *see* integral square error

k

- Kalman filter, single-vial monitoring 102
- kernel structure, rice grain 22
- Knudsen regime, molecular diffusion in 75
- Kohlraush-Williams-Watts equation 263

l

- lactose-based materials, spray-drying 11–12
- lactose particles, low molecular weight substances 238
- large primary suspension particles 244
- large solid particles, suspensions 244
- layered structured granules, breakage behavior 320–321
- layering
 - solidified shells 296
 - spray fluidized bed processes 297
- linear materials, stress-strain relationships 34–36
- linoleic acid, emulsion size 280
- lipid amount, oil emulsions 278
- lipid oxidation, in drying process 7
- lipids oxidation 279–280

- liquid bridges 303–304
 - capillary forces 303–304
 - forces 303–304
 - particle formulation 296
 - tensile strength 309
- liquid distribution, open-pore particle network 220
- liquid drainage 183
- liquid encapsulation, neural networks 357
- liquid flow rate, stochastic discrete modeling 367
- liquid formulation
 - composition of 83–84
 - of pharmaceuticals 53
- liquid/gas interface 175
- liquid penetration time 283
- liquid pressure, drying methods 176
- liquid transport models 212
- local moisture content, calculated by CFD 12
- low hydrated agricultural products, textured by drying 3
- low molecular weight substances
 - solutions 236–240
 - transfer coefficients 237
 - vapor pressure 236
- low-temperature process, CO₂ 187–189
- LyoDriver, primary-drying control algorithm 129–132
- LyoMonitor system, vial batch monitoring 123–124
- lyophilization. *see* freeze-drying
- LYOTRACK sensor, vial batch monitoring 111–112

m

- macropore size, tuning 196
- macroscopic models, convective drying 211–218
- Maillard reactions, in drying process 8
- maltodextrin (MD)
 - investigations by CLSM 247–248
 - mint oil particle size 360
 - orange oil particle size 360
 - pergamot oil particle size 361
 - plasticized surface 305
- mannitol particles 240
- manometric temperature measurement (MTM)
 - and PRA 59
 - primary-drying control 129, 133
 - vial batch monitoring 115, 119–120
- mass balance equation 218
- mass flow rate of water, secondary drying 135–136

- mass spectrometers, vial batch monitoring 107–110
 - material structure, agglomerates 300–301
 - maximum product temperature 126–127, 134
 - Maxwell model, viscoelastic gels 217
 - MC. *see* Monte Carlo methods
 - MDSC. *see* modulated DSC
 - mean product temperature, freeze-drying 61–63
 - melting curves, freeze-drying 54–55
 - mercury porosimetry 168–171
 - mercury pycnometry 171
 - meridian cracks
 - agglomerates 316
 - shells 320
 - mesopore sizes, dry RF gels 192, 194
 - micro-cracks 181
 - microencapsulated flavor powders 245–247
 - microencapsulation
 - enzymes and oil 269–280
 - general remarks on 253–255
 - hydrophilic flavors 255–256
 - oils 278–280
 - by spray drying 269–270
 - microspheres, wet gels 195
 - microtomography 172–173
 - microwave drying, quality preservation 210–211
 - milled rice, obtainment of 22
 - mint oil particle size 360
 - model predictive control (MPC) algorithm, primary-drying control 133
 - modeling
 - agglomeration 363–372
 - convective drying 211–220
 - diffusion 211–217
 - of final quality of rice grains 39–45
 - flavor release 262
 - fluid dynamics in drying chamber 141–142
 - macroscopic 211–218
 - pore-scale 218–220
 - of primary-drying process 125–135
 - rigorous 217–218
 - Wurster coater 349–357
 - modulated DSC (MDSC), freeze-drying 55
 - moisture content. *see also* water content
 - residual 137, 282–283
 - moisture gradients, in freeze-dried matrix 52
 - moisture profiles 208
 - moisture sensors, vial batch monitoring 107–113
 - molecular diffusion, in Knudsen regime 75
 - momentum equation, discrete particle modeling 350
 - monitoring. *see* batch monitoring; primary-drying monitoring; single-vial monitoring; vial monitoring
 - monolithic carbon aerogels, dry gels 161
 - monomer solution, shrinkage prevention 199
 - Monte Carlo (MC) methods
 - agglomeration 363
 - coalescence 366
 - morphology. *see also* ice morphology
 - alcohol dehydrogenase (ADH) powder 248
 - bovine serum albumin (BSA) 250
 - fracture 160
 - high-porosity particles 235
 - hollow particles 235
 - spray-dried particles 231–294
 - spray-dried powders 234–236
 - MPC. *see* model predictive control
 - MTM. *see* manometric temperature measurement
- n**
- NaCl particles 239
 - near-infrared (NIR) spectroscopy
 - residual moisture 283
 - single-vial monitoring 100
 - neural networks
 - artificial 359
 - encapsulation 357–363
 - nitrogen adsorption 166–168
 - NMR. *see* nuclear magnetic resonance
 - non-invasive monitoring techniques, primary drying 98–99
 - non-invasive sensors, freeze drying
 - of pharmaceuticals 86
 - nozzles, spray drying 231
 - nuclear magnetic resonance (NMR) 283
 - nucleation
 - control of 70–73, 94–96
 - freezing process 184
 - nucleation temperature
 - pharmaceuticals 56
 - spontaneous 71
 - and sublimation rates 73–74
 - number density distribution, bed material 326
 - nutritional properties, and food quality 4
- o**
- observation methods, of ice crystal structure 57
 - oil powders 278

- oils
 - encapsulation and microencapsulation 269–280
 - microencapsulation 278–280
 - orange 359
 - particle size 360–361
 - spray drying 278–279
 - thermal stress 271–272
 - yields 361–362
- open-pore particle network, liquid distribution 220
- operating conditions, and sublimation kinetics 79–82
- orange oil
 - in granules 359
 - particle size 360
 - yields 361–362
- organic-inorganic hybrid gels 204
- organic particle sintering 306
- outlet gas handling, apparatus design 332
- oxidation
 - encapsulated flavors 261–269
 - encapsulated lipids 279–280
- oxidation reaction, *D*-limonene 267
- P**
- paddy. *see also* rice grains
 - HRY 23–28
 - quality kinetics 40–44
- parboiled rice
 - HRY 23–28
 - obtainment of 21
- particle. *see also* specific types of particles
- particle collisions, in DPM 351
- particle formulation
 - carrier materials 247–251
 - material properties 299–324
 - operating conditions 324–332
 - spray fluidized beds 295–378
- particle growth rate, total 346
- particle modeling, Wurster coater 349–357
- particle morphology, skin-forming materials 234
- particle porosity, and agglomeration 369–372
- particle retention time 326–327
- particle size
 - distribution evolution 345
 - spray-dried powders 236
 - two-compartment model 348
- particle strength, spray-dried particles 281–282
- passive transponders, in primary-drying monitoring 98
- PAT. *see* Guidance for Industry Process Analytical Technology
- pharmaceuticals
 - freeze-drying 51–86, 91–144
 - key quality factors of freeze-drying 52–63
 - liquid formulation 53
 - nucleation temperature 56
 - polymorphism 84–85
- phase transitions, dependence on drying speed 12–13
- physical quality factors
 - and controlled nucleation 70–73
 - freeze-dried cake morphology 74–78
 - ice morphology 63–69
 - importance of temperature control 78–79
 - influenced by freeze-drying parameters 63–82
 - nucleation temperatures and sublimation rates 73–74
 - operating conditions and sublimation kinetics 79–82
- PI. *see* proportional-integral compensator
- Pirani gauges, vial batch monitoring 106
- plastic breakage behavior 318–320
- plastic range, drying methods 176
- pneumatic dryer, food industry 2
- polymer crosslinking, silica gels 200
- polymer-like gel networks 157
- polymer solutions, vapor pressure 240
- polymers, solutions 240
- polymorphism, and product quality during freeze-drying 84–85
- population balance equation, dispersive growth 344
- population balance modeling 324
- pore-scale model, convective drying 218–220
- pore sizes
 - distribution 331
 - mercury porosimetry 168
 - tomography 172
- wet RF gel 166
- porod regime 163
- porosimetry, mercury 168–171
- porosity
 - dry gels 159
 - particles 369–372
 - spray dried particles 280–281
 - xerogels after pyrolysis 205
- porous carrier particles, loading with catalytic active components 329
- porous media, standard characterization techniques 155
- powdered milk products, rubbery state 11
- powders

- flavor release 262–267
 - layering 298
 - microencapsulated flavor 245–247
 - particle formation 231
 - silica aerogels 191
 - spray drying 234–236
 - stickiness 260–261
 - PRA. *see* pressure rise analysis
 - pressure gradient, differential shrinkage 178
 - pressure rise analysis (PRA)
 - key quality factors 59–61
 - vial batch monitoring 115, 119–120
 - pressure rise test (PRT)
 - primary-drying control 131–132
 - secondary drying 135–136
 - vial batch monitoring 114–125
 - pressure sensors, vial batch monitoring 106
 - primary-drying control
 - chamber pressure 125–135
 - DPE algorithm 129, 132
 - feedback logic 134–135
 - IMC 133
 - in-line 125–135
 - ISE 131, 134
 - LyoDriver 129–132
 - MPC 133
 - MTM 129, 133
 - PI 134
 - PRT 131–132
 - shelf temperature 125–135
 - primary-drying monitoring. *see also* single-vial monitoring
 - active transponders 98
 - BTM 115
 - detection of endpoint 106–113
 - DPE algorithm 115
 - group of vials 103–105
 - in-line 96–125
 - MTM 115, 119–120
 - non-invasive techniques 98–99
 - passive transponders 98
 - RTD 97–99
 - single vials 99–103
 - thermocouples 97–99
 - using measurement of sublimation flux 113–114
 - using methods based on PRT 114–125
 - vial batch 106–125
 - primary particle properties, agglomeration 321–324
 - ProCell units, apparatus design 334–335
 - process analytical technology (PAT), guidance for, in industry 92, 143
 - process chamber, apparatus design 333
 - process temperature, spray fluidized beds 327–329
 - process variables 275–278
 - product flowability, spray dried particles 282
 - product quality. *see also* quality
 - apparatus design 332–338
 - during drying and storage 83–85
 - and formulation 83–84
 - gained by drying 4
 - and polymorphism 84–85
 - product quality control
 - continuous freeze-drying 142–143
 - control of freezing step 94–96
 - control of primary drying 125–135
 - in-line 91–144
 - monitoring and control of secondary drying 135–138
 - monitoring of primary drying 96–125
 - quality by design 139–142
 - product stability, during drying and storage 83–85
 - proportional-integral (PI) compensator, primary-drying control 134
 - protein addition, enzyme stabilization 275
 - protein encapsulation theory 272–273
 - protein loss, surface adsorption 270
 - protein solutions
 - aqueous 51
 - spray drying 273
 - proteins
 - particle creation 247–251
 - stress during the spray drying processes 270–272
 - stresses 271
 - proton transfer reaction mass spectrometry (PTR-MS), flavor release 266
 - PRT. *see* pressure rise test
 - PTR-MS. *see* proton transfer reaction mass spectrometry
- q**
- QMS. *see* quadrupole mass spectrometer
 - quadrupole mass spectrometer (QMS), vial batch monitoring 107–110
 - quality *also* food quality; product quality
 - modeling of convective drying 211–220
 - quality assessment, gels 162
 - quality by design 139–142
 - quality considerations, drying food materials 1–18
 - quality control, in-line 91–144
 - quality factors. *see also* physical quality factors
 - interactions with transport phenomena 53
 - quality loss, gel drying methods 174–189

- quality preservation
 - advanced drying techniques 189–211
 - carbon cryogels 192
 - convective drying 198–210
 - cracks from aging 199–201
 - ice templating 195–197
 - microwave drying 210–211
 - RF gels 192, 204–209
 - shrinkage reversion 201–204
 - silica gels 195–197
 - vacuum drying 197–198

r

- radiation from surrounding, as quality parameter 139
- re-agglomeration 284
- reconstitution behavior, spray dried particles 283–284
- rehydration, during storage 16–17
- relative humidity (RH)
 - flavor release rate 264
 - lipid oxidation 279
 - and rice fissuring 24–25
- relaxation function 216
- relaxation process correlation
 - glass transition temperature 267–269
 - temperatures 267–269
- residence time distribution 338–344
- residual moisture content
 - infrared irradiation 282
 - spray dried particles 282–283
- residual water content, monitoring of 91–92, 137–139
- resistance thermal detector (RTD), in primary-drying monitoring 97–99
- resorcinol-formaldehyde (RF) gels
 - aging 208–209
 - convective drying 206
 - freeze drying 191
 - linear shrinkage 209
 - preparation 156–158
 - quality preservation 192, 204–208
 - saxs spectra 164
 - synthesis 158
- restitution coefficient 351
- retention
 - emulsified hydrophobic flavors during spray drying 257–260
 - enzyme activity 275
- retention phenomenon, at microscopic level 10
- retention time, particles 326–327
- RF gels. *see* resorcinol-formaldehyde gels
- RH. *see* relative humidity

- rice
 - characterization of mechanical properties 33–39
 - HRY 23–28
 - image analysis techniques 28–33
 - mechanical properties and crack formation 21–45
 - tempering time 27–28
 - rice bran, obtainment of 22
 - rice grains. *see also* paddy
 - dehulling 22
 - diametral compression test 37
 - failure strength 36–39
 - glass transition 34
 - gray level histograms 29
 - harvesting 21
 - Hooke's law 34
 - kernel structure 22
 - moisture content 21–22
 - stress-strain relationships 34–36
 - Young's modulus 35
 - rice kernels
 - cracks in 23
 - fissured 23–24
 - possible states for 24
 - shrinkage and cracking 29
 - stress cracks 39
 - structure 22
 - tension tests 37–38
 - rice processing yield, definition 23
 - rice quality
 - kinetics 40–44
 - modeling of 39–45
 - rolling agglomeration 318
 - rotary dryer, food industry 2
 - rotational motions, amorphous glass state 261
 - rough rice. *see* rice grains
 - rubbery state, of freeze-dried materials 11
- ## **s**
- safety, and food quality 4
 - Sauter mean diameter, reconstitution behavior 283
 - SAXS. *see* small angle X-ray scattering
 - SBS. *see* styrene-butadiene-styrene
 - scanning electron microscopy (SEM), spray-dried particles 234
 - secondary drying, monitoring and control 93, 135–138
 - segmentation method, image analysis techniques 30–31
 - selective diffusion, in drying process 10

- selective diffusion theory, hydrophilic flavors 255
- self-assembly techniques, gelation 156
- SEM. *see* Scanning electron microscopy
- sensors
 - LYOTRACK 111–112
 - for mean-product-temperature measurements 61–63
 - moisture 107–113
 - non-invasive 86
 - pressure 106
 - soft 101–102
- sensory properties, and food quality 4
- SEP function, sublimation endpoint detection 112
- series-of-tanks model 340
- shear stress 271–272
- shelf temperature. *see also* temperature
 - BTM control 128–129
 - influence on drying curve 79–80, 82
 - primary-drying control 93, 125–135
 - as quality parameter 139
- shrinkage
 - aged gels 200
 - aging effects 209
 - by convective hot air drying 15
 - differential 177–180
 - diffusion models 213
 - drying methods 177
 - freezing process 184
 - gels 175–177
 - irreversible 169
 - isotropic 206
 - linear 209
 - pore sizes 168
 - prevention 199–201
 - reversion 201–204
 - video acquisition 29
- silica gelation, condensation 156
- silica gels
 - ice templating 195–197
 - polymer crosslinking 201
 - preparation 156–157
 - shrinkage prevention and cracks by aging 199–201
 - shrinkage reversion 201–204
- silylation agents 203
- Si₃N₄-suspensions, spray-dried particles 243
- single suspended droplet, drying 273–274
- single-vial monitoring
 - extended Kalman filter 102
 - high gain observers 102
 - in-line 99–103
 - soft-sensors 101–102
- sinter bridges 304–308
 - forces 304–308
 - viscous forces 304–308
- sintering
 - mechanisms 305
 - organic particle 306
- skeletal density
 - RF gels 191
 - shrinkage prevention 199
- skin-forming materials, particle morphology 234
- small angle X-ray scattering (SAXS), drying of gels 162–164
- small solid particles, suspensions 240–244
- smart-vial concept 98, 103
- SMART™ Freeze-Dryer 129
- sodium benzoate granules
 - breakage 320–321
 - force-displacement curves 320
- soft-sensors, single-vial monitoring 101–102
- solid network stress, drying methods 176
- solid particles
 - suspensions of large 244
 - suspensions of small 240–244
- solid pharmaceutical substances, preparation 269
- solid phase, diffusion models 212
- solids, diffusion rate 241
- solids handling, apparatus design 332
- solutions
 - binder content 325–326
 - low molecular weight substances 236–240
 - polymers 240
 - spray drying 273
- solvent exchanges
 - RF and carbon cryogels 193
 - TMCS surface modification 203
- solvents, supercritical drying 185–187
- sound insulation, dry gels 161
- sound speed, dry gels 160
- space science, dry gels 162
- specific surface area, dry gels 159
- spectroscopy methods, single-vial monitoring 100
- spontaneous nucleation temperatures 71
- spout velocity 352–355
- spray-dried food products
 - flavor retention 253–269
 - ingredients 233
- spray-dried particles
 - β -lactoglobulin effects 250
 - BSA effects 250
 - bulk density 282
 - compression 311

- emulsions 246
- freeze spray drying 251–253
- hard shell 244–245
- integrated fluidized beds 253
- lipids oxidation 279–280
- morphology and properties 231–294
- porosity 280–281
- proteins, enzymes and carrier materials 247–251
- quality aspects 280
- schematic view 269
- spray-dried 231–294
- structures 246
- surface structure 239
- suspensions of large solid 244
- suspensions of small solid 240–244
- spray-dried powders
 - cross-sectional structures 248
 - flavor release 262–267
 - morphological characteristics 233
 - morphology 249
 - morphology classification 234–236
 - outer structural changes 266
 - stickiness 260–261
- spray dryer, food industry 2
- spray drying
 - emulsified hydrophobic flavors 256–257
 - encapsulation and microencapsulation of enzymes and oil by 269–280
 - enzyme stabilization 274–275
 - flavor encapsulation 255
 - of lactose-based materials 11–12
 - microencapsulation 269–270
 - oil emulsions 278–279
 - particle creation 251–253
 - process variables effect on the stabilization of enzymes 275–278
 - protein encapsulation theory 272–273
 - protein solutions 273
 - retention 257–260
 - stress on proteins 270–272
- spray-drying system
 - scheme of 232
 - stresses 271
- spray fluidized bed encapsulation, aromatic oils 358
- spray fluidized bed processes 297
- spray fluidized beds
 - apparatus design 332–357
 - particle formulation 295–378
 - periphery 332
- spray system, apparatus design 333
- sprayed solutions, binder content 325–326
- springback, convective drying 204
- stability, during drying and storage 83–85
- stability diagram, of foods 2
- stabilizer, role of 83
- starch
 - gelinization 245
 - mint oil particle size 360
 - orange oil particle size 360
 - pergamot oil particle size 361
- state diagram, freeze-drying 54–55
- stickiness, spray-dried powder 260–261
- stochastic discrete modeling 364–367
 - agglomeration 363–372
- storage
 - of food materials 16–17
 - product quality and stability during 83–85
 - release and oxidation of encapsulated flavor 261–269
- storage stability, glass temperature influence 261–262
- strain difference, diffusion models 213
- strength
 - agglomerates 299–315
 - particles 281–282
- stress
 - and differential shrinkage 177–180
 - diffusion models 213
 - on proteins during drying 270–272
 - simulations 215
- stress cracks, in rice kernels 39
- stress-strain relationships, rice grains 34–36
- styrene-butadiene-styrene (SBS) latex 241
- subcritical drying, quality preservation 189–190
- sublimation chamber. *see also* drying chamber
 - gas pressure and drying curve 79–81
 - heat flux heterogeneity in 57–59
 - total gas pressure 117–118
- sublimation endpoint detection, vial batch monitoring 106–113, 121–122
- sublimation flux measurement, vial batch monitoring 113–114
- sublimation front temperature 62
- sublimation kinetics, and operating conditions 79–82
- sublimation rates, and nucleation temperatures 73–74
- sudden expansion, combined with drying 18
- sun-cracks, rice 24
- supercapacitors, dry gels 161
- supercooling, and ice morphology 55, 63
- supercritical drying
 - gels 159, 185–189
 - heating rate 185
 - initial solvent 185–187

- RF and carbon cryogels 192
- washing step 187
- surface cracking, during drying 16
- surface cracks, rice 25
- surface modification
 - quality preservation 201–204
 - TMCS 203
- surfactants, enzyme activity retention 275
- suspension droplets
 - drying 273–274
 - glass deposition 245
- suspensions
 - fine glass filament 272
 - flash spray drying 242
 - large solid particles 244
 - small solid particles 240–244
- syneresis, silica gelation 157

t

- TDLAS. *see* tunable diode laser absorption spectroscopy
- temperature. *see also* chamber temperature; shelf temperature
 - influence on crack formation in rice 26–27
- temperature control, and physical quality 78–79
- temperature increase, and biochemical reactions in foods 5–9
- temperature remote interrogation system (TEMPRIS) 98
- tempering time, rice 27–28
- tension tests, rice kernels 37–38
- TEOS. *see* tetraethoxysilane
- tert-butanol, microwave drying 210
- tert-butanol (CH_3)₃COH, freeze drying 191
- tetraalkoxysilane $\text{Si}(\text{OR})_4$ 156
- tetraethoxysilane (TEOS) 156
- tetramethoxysilane (TMOS) 156
- thermal conductivity gauges, vial batch monitoring 106
- thermal effects, stochastic discrete modeling 367–369
- thermal stress, enzymes and oil 271–272
- thermocouples
 - insertion in vials 61
 - in primary-drying monitoring 97–99
- thermograms, with ultrasound triggered nucleation 71
- thermoporometry 164–166
- three-layer artificial neural network 359
- time step length, MC methods 364
- TMCS. *see* trimethylchlorosilane
- TMOS. *see* tetramethoxysilane
- total gas pressure, sublimation chamber 79–81, 117–118
- transmission electron microscopy, characterization of gels 171
- transport phenomena, interactions with quality factors 53
- trimethylchlorosilane (TMCS)
 - shrinkage reversion 202
 - solvent exchanges 203
- tunable diode laser absorption spectroscopy (TDLAS), vial batch monitoring 113–114
- tunnel conveyor dryer, food industry 2
- two-compartment model
 - fluidized bed 347
 - particle size distributions 348
- two population balance equations 348

u

- ultrasonic atomizers, spray drying 231
- ultrasonic irradiation, gelation 195
- ultrasound, effect on structural and morphological properties 72–73
- ultrasound triggered nucleation
 - controlled 70–72, 95–96
 - human recombinant interferon 96–97
- thermograms 71
- undercooling 165

v

- vacuum drying
 - gels 184
 - quality preservation 197–198
 - RF and carbon cryogels 192
- van der Waals forces
 - adhesion 299
 - agglomerates 301–303
- ventilated cabinets drying, food industry 2
- vial monitoring
 - single vials 99–103
 - vial batches 106–125
 - vial groups 103–105
- vial type, influence on ice morphology 66–67
- vials
 - for freeze-drying of pharmaceuticals 51–86
 - heat transfer coefficient 58–59
- video acquisition, of shrinkage and cracking of rice kernels 29
- viscoelastic gels, Maxwell model 217
- viscosity
 - shift factor 301
 - stochastic discrete modeling 367
- viscous forces
 - adhesion 299
 - between amorphous particles 304–308

- viscous solid network, differential shrinkage 179
 - visual inspection, compared to image analysis 32–33
 - vitamin C. *see also* ascorbic acid
 - as a quality index in drying process 6
 - vitreous transition, freeze-drying 54–55
 - vitrification concept, product stabilization 83
 - volatile flavors 255
 - volume-averaged liquid density, transport models 212
 - VPO precursors 244
- W**
- Washburn equation 168
 - water activity
 - decreasing 1
 - and enzymatic activity 8
 - and stability diagram of foods 2
 - water concentration, time evolution
 - measurements 107–113, 136–137
 - water content. *see also* moisture content
 - residual 91–92, 137–139
 - water flow rate, secondary drying 135–136
 - water layer hypothesis, protein encapsulation 271
 - water replacement hypothesis, protein encapsulation 271–273
 - water-soluble crystalline substances 304
 - water substitute concept, product stabilization 83
 - water vapor mass transfer resistance
 - and freeze-dried cake morphology 74–76
 - and freeze-dried layer thickness 69, 76
 - water vapor pressure, in drying chamber 62
 - wet gels
 - characterization 162–166
 - preparation 156–158
 - white rice, obtainment of 22
 - whole-batch monitoring, freeze-drying 106–125
 - Williams, Landel and Ferry (WLF) equation 267, 301
 - wireless probes, in primary-drying monitoring 98
 - Wurster coater
 - discrete particle modeling 349–357
 - gap distance 355–357
 - geometry 352
 - particle positions 353–356
 - schematic representation of 334
 - velocity distributions 353–356
- X**
- X-ray tomography, drying gels 172
- xerogels**
- definition 159
 - mercury porosimetry 170
 - vacuum drying 198
- Y**
- Young's modulus
 - rice grains 35
 - time-dependent 36
- Z**
- zeolite agglomerates 317–319