

Index

a

adaptive Lagrangian time step 170
 advection terms, population
 balances 213
 aerodynamic interaction, stochastic
 collisions 186
 age of particles 211
 agglomeration 187–189, 191
 –particle tracking 170
 –population balances 212
 –spray-dryer simulation 161,
 199
 aggregation 225–233
 –and growth 244–245
 –and nucleation 243–244
 aggregation-breakage coupling
 239–243
 aggregation, population balances 231
 air conservation 6
 air flow
 –spray-dryer simulation 160
 –stack model 46
 airtight sensors 26
 algebraic turbulence models 157
 algorithm description, droplet
 drying 179
 alternative tree-search approach 292
 alumina, continuous
 thermomechanical drying 107
 ancillary calculations 283–287
 Archimedes buoyancy 168
 Arnoldi process 17
 Arnoldi vectors 18
 Aspen process manual 295
 assumed elastic behavior 115–120
 atomization, spray-dryer
 simulation 162, 193
 averaged internal equations
 –balance 113

–continuous thermomechanical

 drying 107
 –Darcy's law 110
 –energy conservation 112–113
 averaging theorem 3, 5

b

balance equations 213–215
 –averaged internal 113
 –global 126–130
 –stack model 46
 basic scale-up principles 273–274
 Basset-Bousinesq-Oseen (BBO) particle
 tracking 169
 Basset history force 168
 batch-contact dryers 271
 batch dryers 270–271
 batch lumber kiln 45, 47
 BBO *see* Basset-Bousinesq-Oseen
 beech, volume averaging 42
 bimodal networks 97
 –heat transfer 91
 –isothermal drying models 86
 bimodal pore-size distributions 95–100
 binary breakage, population balance
 equation 220–221
 body deformations 143–144
 Bond number 75
 Borel's convolution formula 142
 bound-water diffusion 6
 bound-water flux 7
 boundary conditions
 –convective drying 113–114, 145
 –generalized Darcy's law 7
 –moving sectional methods 237
 –spray-dryer simulation 160
 boundary layers
 –drying curves 85
 –isothermal drying models 60–62

- thickness 69
- breakage-aggregation coupling 239–243
- breakage function 214
- breakage process, finite-volume scheme 222
- British standards (BS), humidity calculations 284–286
- burning period, microwave heating 31
- c**
- calculation programs, software types 263
- calculations complexity, development barriers 297
- capillary number
 - length scales 76
 - wettability effects 84
- capillary pressure 143
 - heat transfer 88
 - isothermal drying models 64
 - length scales 75
- capillary pumping
 - isothermal drying models 64–65
 - pore structure influence 98
- carpet plots
 - radio-frequency heating 34
 - softwood drying behavior 29, 32
- cascading rotary dryers 281
- CDC *see* characteristic drying curve
- CDRP *see* constant drying rate period
- cell-average mechanism 219
- cell-average technique 227–230, 239
 - population balance equation 216–222
- CFD *see* computational fluid dynamics
- characteristic drying curve (CDC) concept 267
- characteristic lengths 76
- chemical potential
 - balance equations 129
 - convective drying 145
 - rate equations 134
 - thermohydromechanical drying 139
- circumferential stresses
 - convective drying 148–159
 - microwave drying 151
- Clausius–Clapeyron equation 175
- clusters 63
 - isothermal drying models 72
 - labeling 65
- coagulation, pure aggregation 228
- coalescence 187–189
- collector efficiency, stochastic collisions 186
- collision number 198
- collisions
 - dry particles 161, 189–192
 - particle 181–192
 - probability 185
 - stochastic modelling 182–187
- commercialization, drying software 296–301
- complex three-dimensional models 276
- comprehensive drying 1–52
- computational fluid dynamics (CFD) 281–283
 - collisions of particles 181–192
 - dissipation rate 156
 - droplet-drying models 173–181
 - Euler–Lagrange approach 162–173
 - examples 192–200
 - prediction of product properties 200–203
 - spray-dryer simulation 155–208
- concrete, high-temperature convective drying 19–25
- condensation, heat transfer 89
- connectivity of pores 59, 94
- conservation
 - air 6
 - energy 7
 - numerical resolution technique 114
 - water 6
- conservation equations 15–17, 107–112, 121–122, 156–158, 192
 - Reynolds-averaged 156
- conservation law
 - balance equations 128
 - finite-volume scheme 222
- constant drying flux period 8
- constant drying rate phase 8–9, 140
- constituent velocity of moisture 126
- constitutive equations 130–132
- continuity equation
 - gas phase water vapor 4
 - liquid phase 3
 - volume averaged 5
- continuous contact dryers 270–271
- continuous convective dryers 269–270
- continuous fluidised bed dryer 210–211
- continuous models 100–101
- continuous-phase source terms 163
- continuous thermohydromechanical models 125–154
- continuous thermomechanical models 103–124
 - simulation 114–120

- control volume 45
 - deformable 127
- control-volume finite-element (CVFE) discretization procedure 12–14
 - discretization process 17
- convective drying 18–29, 107
 - boundary conditions 113–114
 - heat transfer 58
 - high-temperature 19–25
 - IDC 33, 35
 - isothermal drying models 60
 - kaolin cylinder 144–149
 - low-temperature 7–10
 - radio-frequency heating 34
- convective flux 24
- cooling effect, surface evaporation 91
- coordinate space, total 210
- coordination number, pore structure influence 94–95
- corner films, film flow 80
- corner flows 93
- coupling
 - breakage aggregation 239
 - Euler–Lagrange approach 159
 - stack model 46
- creep 142
- creep strain, thermohydromechanical drying 134
- cumulative size distributions, stochastic collisions 183
- Curie–Prigogine symmetry principle 133
- CV face 14–15
- CVFE *see* control-volume finite-element
- d**
- damping coefficient, microwave heat source 137
- Darcy's law 7
 - averaged internal equations 110
- data structures, isothermal drying models 59–60
- databanks, physical properties of dryers 287
- decision-making tools 289–295
- decomposition, volume-averaging models 5
- decreasing drying rate phase 9
- deformable materials, drying behaviour 34–37
- deformation gradient tensor 36
- deformations, thermohydromechanical drying 125
- density, volume-averaging models 4
- depth scalar, generalized Darcy's law 7
- design models, detailed 276–277
- desorption, averaged internal equations 113
- destruction, microwave drying 151–152
- deviation variables, volume-averaging models 5
- dielectric properties, microwave heat source 137
 - thermohydromechanical drying 126
- differential equations, thermohydromechanical drying 134–141
- diffusion
 - fluid phase modeling 163
 - identity drying card 33
 - isothermal drying models 58
 - milk drying 178
 - moving sectional methods 237
 - volume-averaging models 6
- diffusion coefficient
 - milk drying 176
 - particle morphology 202
- diffusion tensors 14
- diffusivity
 - identity drying card 33
 - vapor phase 5
 - volume-averaging models 6
- Dirac-delta distribution 215
- direct numerical simulations (DNS) 155
- discontinuous Heaviside function 218
- discretization
 - finite-volume scheme 223
 - procedure 13–14
 - pure breakage 215
 - pure growth 234
- dispersed phase results 195–200
- dispersed phase source terms 163
- dispersed two-phase flows 159
- dispersive transport, volume-averaging models 5
- displacement, balance equations 127
- displacement fields, periodic 41
- dissipation rate 156
- DNS *see* direct numerical simulations
- domain discretization 251
- double coordinates system, homogenization 38
- drag coefficient 170
- drag forces
 - Lagrangian particle tracking 167
 - VD collisions 191
- driving forces 146

- droplet density 178
 - droplet-drying models 173–181
 - numerical
 - implementation 178
 - review 175–176
 - droplet evaporation 175
 - droplet interaction 190
 - droplet size 160
 - droplets dominated by viscous forces (VD droplets) 188
 - dry particles
 - collisions 161, 189–192
 - solid 184
 - dry patches distribution 71
 - dry solids, enthalpy 181
 - dryer designs 157
 - software 301
 - dryer geometry 192–193
 - dryer length 270
 - dryer models
 - categorization 264
 - comparison 266
 - dryer selection 289–294
 - dryers
 - continuous contact 270–271
 - continuous convective 269–270
 - continuous fluidised bed 210
 - scale up 157
 - troubleshooting and problem solving 294–295
 - drying
 - at high temperature 10
 - convective 7–10
 - definition 103
 - pore level 57–102
 - quality 50–51
 - drying air, isothermal drying models 61
 - drying algorithm 66–69
 - drying behavior
 - highly deformable materials 34–37
 - potato 36
 - softwood 25–29
 - drying body 141–144
 - drying conditions 45
 - drying conservation equation 15
 - drying curves
 - boundary layer influence 85
 - convective drying 147
 - length scales 77–79
 - normalization 275
 - pore structure influence 95–96
 - drying front 21, 71
 - drying kinetics 57–102
 - drying models 1–52
 - drying periods
 - constant rate 140
 - dynamic equilibrium 9
 - falling rate 140
 - microwave heating 30
 - transition for light concrete 20
 - drying process duration
 - severe conditions 24
 - soft conditions 22
 - drying software 261
 - commercialization 296–301
 - development barriers 297–298
 - drying technology 155–208
 - drying theory and practice, gap 262
 - dual-scale models 47
 - Duhamel-Neuman equation 132
 - dynamic equilibrium, drying phases 9
- e**
- ECM *see* equilibrium moisture content
 - EDECAD *see* efficient control and design of agglomeration during spray drying
 - effective diffusivity tensor, volume-averaging models 6
 - effective stress 130–131
 - efficient control and design of agglomeration during spray drying (EDECAD) 176
 - elastic behavior 115–120
 - elastic case 104
 - elastic deformations 130
 - electric conductivity, microwave heat source 135
 - electric field intensity, microwave heat source 136
 - electromagnetic heating, less common drying configurations 30
 - EMC *see* equilibrium moisture content
 - energy absorption, microwave heat source 137
 - energy balance 129
 - energy conservation
 - averaged internal equations 112–113
 - volume-averaging models 7
 - enthalpic period, microwave heating 30
 - enthalpy
 - continuous fluidised bed dryer 211
 - desorption 113
 - dry solids 181
 - per unit mass 113
 - pore network models 87

- stack model 46
 - vapor 113
 - entropy
 - balance equations 128
 - time derivative 134
 - EOC *see* order of convergence
 - equations
 - averaged internal 107–113
 - balance 46, 50, 113, 126–129, 213–215, 277
 - Clausius–Clapeyron 175
 - conservation 15–17, 107–112, 121–122, 156–158, 192
 - constitutive 130–132
 - continuity 3–5
 - differential 134–141
 - drying conservation 15
 - Duhamel–Neuman 132
 - gas-phase water vapor
 - continuity 4–5
 - Gibbs 130–131, 134
 - Gibbs–Duhem 132, 140
 - heat-balance 277
 - Heaviside function 229
 - Hoshen–Kopelman
 - algorithm 65
 - liquid phase continuity 3
 - macroscopic set 6–7
 - mass-balance 277
 - mass-conservation
 - 109–112
 - Maxwell 30, 135
 - momentum 6, 156
 - momentum conservation
 - 103–105, 109–114, 120–122
 - particle transport 277
 - population balance 210, 214–225, 233
 - pressure linked 165
 - rate 132–134
 - Reynolds 156
 - Reynolds-averaged Navier–Stokes 155, 163
 - state 108, 131
 - thermomechanical 141–144
 - total momentum
 - conservation 110
 - transport 1–5, 82, 163–166
 - two-equation models 157
 - water-vapor transport 1
 - wave 136
 - equilibrium contact angle, wettability effects 83
 - equilibrium moisture content (ECM) 26
 - equilibrium solvent concentration, droplet drying 180
 - equilibrium vapor pressure reduction, isothermal drying models 58
 - equipment models, drying software 265–266
 - error progression, fluid phase modeling 165
 - Euler–Euler approach 158
 - Euler–Lagrange approach 162–173
 - flow chart 174
 - multiphase flow modeling 159
 - particle collisions 181
 - Euler's description, balance equations 126
 - Eulerian correlation tensor 172
 - Eulerian time scale 170
 - evaporation , 140
 - film flow 80
 - solvent 201
 - thermohydromechanical drying 135
 - evaporation rates 63, 85
 - heat transfer 88
 - experimental data processing 283
 - experimental order of convergence (EOC) 220
 - expert systems 289–295
 - external coordinates, population balances 210
 - external pressure decrease 10
- f**
- falling-rate drying 271–272
 - falling-rate period 140
 - FDI *see* flow direction indicator
 - fictitious particles 183–184
 - field forces, Lagrangian particle tracking 167
 - film flow, pore networks 79–83
 - finite-volume scheme 222–225, 231–232
 - first drying period 85–87
 - drying phases 8
 - heat transfer 90
 - fixed-pivot technique
 - aggregation nucleation coupling 244
 - pure aggregation 226–227
 - pure breakage 215
 - flow chart
 - Euler–Lagrange approach 174
 - isothermal convective drying 67
 - menisci identification 74
 - flow direction indicator (FDI) 15
 - flow-field pattern, spray-dryer simulation 193
 - fluctuation velocity 171
 - fluid-dynamic forces 166
 - fluid-phase modeling 163–166
 - fluid-phase results, spray-dryer simulation 193–195

- fluidized-bed dryers 274–276
 flux limiting, tensor evaluation 14
 flux-limiting methods, pure
 growth 234
 fluxes, continuous thermomechanical models 113
 Fourier's law 112
 free liquids, isothermal drying models 58
 french fry, moisture content field 37
 friction
 -characteristic lengths 76
 -drag force 167
 -length scales 75
- g**
 gap, drying theory and practice 262
 gas-flow patterns 158, 283
 gas permeability tensor 6
 gas-phase properties, droplet
 drying 179
 gas-phase water vapor continuity equation 4–5
 gas-phase water-vapor transport equations 1
 gas pores, mass balances 63
 gas pressure 58, 64
 gas velocity contour 195–196
 gaseous pressure, total 10
 Gauss divergence theorem 13
 Gauss-Ostrogradsky theorem 128
 Gaussian random number 184
 gels, continuous thermomechanical
 drying 106
 general transport theorem 3
 generalized Darcy's law 7
 geometry, spray dryer 192
 Gibbs' equation 130–131, 134
 Gibbs–Duhem equation 140
 Gibbs–Duhem relationship 132
 glass-transition temperature, particle collisions 189
 global balance equations 126–130
 globally convergent Newton's method 16
 GMRES 17
 gravitational effects, length scales 75–76
 gravitational force, Lagrangian particle tracking 169
 gravity modeling 71–74
 gravity potential
 -isothermal drying models 72
 -rate equations 134
 growth and aggregation 244–245
 growth and nucleation 245–247
- h**
 Haines jump 74
 heartwood, drying behavior 25–29
 heat and mass balances 268–269
 heat and mass transfer
 -differential equations 134–141
 -rate equations 132–134
 heat and vapor transfer 8
 heat-balance equations 277
 heat capacity 87
 heat conservation, numerical resolution technique 114
 heat damage, product properties prediction 201
 heat-damage index number 201
 heat flow, milk drying 177
 heat-flow rate 88
 heat transfer
 -bimodal network 91
 -capillary pressure 88
 -condensation 89
 -continuous contact dryers 270
 -convective drying 58
 -evaporation rates 88
 -first drying period 90
 -isothermal drying models 58
 -milk drying 176
 -pore network models 87–92
 -surface evaporation 91
 -thermohydromechanical drying 132–134
 -time discretization 89
 -vapor condensation 89
 heating period, microwave 30
 heating power, microwave 139
 Heaviside function
 -discontinuous 218
 -pure aggregation 229
 high-resolution schemes, pure growth 234
 high-temperature drying 10–13
 -convective 19–29
 highly deformable materials, drying behaviour 34–37
 homogenization 37–42
 homogenized properties 40
 Hoshen-Kopelman algorithm 65
 humidity calculations 284–287
 -British standards 284
 hydraulic conductivity, film flow 80
 hydrophilic porous media 84
 hydrophobic porous media 84

- i**
- identity drying card (IDC) 32–33
 - typical diagrams 35
 - impact efficiency, stochastic collisions 186
 - incremental models 276–278
 - induction, microwave heat source 136
 - industrial design, drying software 262
 - inertia parameter, stochastic collisions 186
 - information loss 165
 - inner iterations 17–18
 - instantaneous strains 142
 - integral models, scale up
 - principles 274–276
 - interfacial tension forces 187
 - internal coordinates, population balances 209
 - internal energy, balance equations 129
 - internal moisture transfer 26
 - internal overpressure 6
 - internal pressure, drying phases 10
 - internet websites, knowledge bases 295–296
 - intrinsic averages 3
 - invasion percolation, pore structure influence 98
 - irreversible deformations
 - constitutive equations 130
 - rate equations 132
 - isothermal convective drying, flow chart 67
 - isothermal drying models
 - boundary layers 60–62, 69
 - capillary pressure 64
 - data structures 59–60
 - pore network models 58–87
 - iterations
 - inner 17–18
 - outer 16–17
- j**
- Jacobian matrix 17
- k**
- kaolin cylinder, convective drying 144–152
 - $\kappa-\epsilon$ turbulence models 157, 163
 - Kelvin effect
 - isothermal drying models 58
 - length scales 76
 - kinematic viscosity 156
 - kinetic energy transport 166
 - knowledge bases, process-systems simulation 295–296
 - Knudsen effect
 - isothermal drying models 58
 - length scales 76
 - Kolmogorov length scale 156
 - Krylov methods 18
- l**
- labeling, clusters 65
 - lack of replicability 298–301
 - Lagrangian particle tracking 166–169
 - Lagrangian time scale 171
 - Lagrangian time step
 - adaptive 170
 - droplet drying 179
 - large eddy simulations (LES) 155
 - large shrinkage values 36
 - latent heat, thermohydromechanical drying 135
 - lateral nondimensional displacement 187
 - layering concept, drying software 265
 - layering models, dryer models
 - categorization 264
 - length scales
 - isothermal drying models 75–77
 - turbulent dispersion modeling 172
 - LES *see* large eddy simulations
 - less-common drying 29–30
 - radio-frequency heating 34
 - volume-averaging models 29–37
 - volumetric heating 29
 - level of complexity, dryer models
 - categorization 264
 - light concrete, high-temperature convective drying 19–25
 - limited market 298–301
 - line-search strategy 16–17
 - linearized system iterations 17
 - liquid cluster, isothermal drying models 72
 - liquid distribution, thermohydromechanical drying 139
 - liquid flow, drying phases 12
 - liquid mass flow rates, isothermal drying models 73
 - liquid mobility tensor 14
 - liquid permeability tensor 6
 - liquid phase
 - continuity equation 3
 - isothermal drying models 64–65
 - volume-averaging models 1
 - liquid pressure 120–122
 - isothermal drying models 64

- liquid redistribution, isothermal drying models 74
- liquid velocity, length scales 75
- liquid viscosity, pore network models 71–72
- liquid volume fraction 111
- liquid water fluxes, stack model 46
- liquid/air interface 62
- liquid/gas interface 86
- local fluxes, stack model 46
- local mass balance 139
- local thermal equilibrium 126
- local thermodynamic equilibrium, absence 42
- low-temperature convective drying 7–10
- lumber drying 11
- m**
- macrochannels 86
- macromolecular gels, continuous thermomechanical drying 106
- macroscopic equations, volume averaging 6–7, 42–43
- macroscopic properties, homogenization 39
- macrothroats 98
- magnetic permeability, microwave 136
- magnetic viscosity, microwave 136
- Magnus force 168
- mass balance
- equations 129, 277
 - pore network models 63
- mass change rate 126
- mass concentration,
- thermohydromechanical drying 126
- mass conservation, numerical resolution technique 114
- mass-conservation equations 109–112
- mass content, thermohydromechanical drying 126
- mass flow, milk drying 177
- mass flow rate
- droplet drying 180
 - isothermal drying models 73
- mass transfer
- drying phases 10
 - fluid phase modeling 164
 - Gibbs-Duhem equation 140
 - menisci 140
 - milk drying 176
- thermohydromechanical drying 132–134, 139
- mass-transfer coefficient 61
- material models, drying software 265
- matrix-type rule-based algorithms 289
- Maxwell equations
- less common drying configurations 30
 - microwave heat source 135
- Maxwell model 142
- mean particle volume, multidimensional population balances 250
- mechanosorptive strain 142
- drying quality 50
- menisci
- drying front 71–77
 - film flow 81
 - heat transfer 88
 - identification 74
 - isothermal drying models 63–66
 - mass transfer 140
- MeshPore 41
- method of lines (MOL) 233
- microscopic foundations
- homogenization 39
 - volume-averaging models 1–6
- microwave drying 150–152
- IDC diagrams 35
 - less common drying configurations 30
 - softwood 33
- microwave heating 135–139
- absorbing properties 136
 - burning period 31
 - convective drying 148
 - drying phases 11, 30
- microwave power 138
- microwave propagation 150
- milk drying, diffusion 176, 178
- milk products, drying models 176–178
- minimum shell diameter, droplet drying 178
- mixing length, fluid phase modeling 166
- mixtures, thermohydromechanical drying 125–154
- mobility tensor 15
- model description, isothermal drying 58–67
- model extensions, pore network 87–92
- modeling depth, spray-dryer simulation 192
- moist air flow 19, 22–25
- moisture, continuous fluidised bed dryer 211
- moisture content 115, 140
- population balances 213
- moisture content curves, stack model 48
- moisture content evolution, stack model 51
- moisture content fields 44
- drying behaviour 37

- moisture content loss, softwood drying behavior 28
- moisture content profiles 119
- moisture content variation, pneumatic conveying dryer 280
- moisture distribution, convective drying 147
- moisture flux 126
- moisture-time drying curve, scale up principles 273
- moisture transport coefficient 140
- moisture two-dimensional predicted fields 116–118
- MOL *see* method of lines
- molecular viscosity 166
- Mollier chart 286
- momentum-conservation equations –averaged internal 109–112
–continuous thermomechanical drying 103
–numerical resolution technique 114
- momentum equations 156
–volume-averaging models 6
- MorphoPore 41
- moving sectional methods 237
- multicomponent liquid 92
- multicomponent medium, entropy 128
- multidimensional population balances 247–255
- multimodal temperature, errors 185
- multiphase drying processes 155
- multiphase flow modeling 158–160
- multiphase systems, continuous thermomechanical drying 103
- multiphase transport, thermohydromechanical drying 125
- multiple surfaces, drying conditions 45
- multiscale approach, model calculation 42–51
- n**
- narrow radius distribution 75
- net flux, multidimensional population balances 251
- network flux, balance equations 127
- network geometry, isothermal drying models 59–60
- network heat flux, rate equations 133
- network size, isothermal drying model 75
- new dryers, software 301
- newborn particles 217, 228, 239
- Newton step 16
- nonlinear functions 15–18
- normalization 275
- Norway spruce 25
- nucleation and aggregation 243–244
- nucleation and growth 245–247
- number density
–multidimensional population balances 247
–pure aggregation 228
- numerical calculation procedures, dryers 263–268
- numerical flux, finite-volume scheme 223
- numerical implementation, droplet-drying models 178
- numerical methods, pure aggregation 226
- numerical resolution technique, continuous thermomechanical models 114
- o**
- oak
–model calculation 41
–soaking wood samples 42
- Ohnesorge number
–STD droplets 187
–VD droplets 188
- one-equation models, turbulence 157
- one-way coupling, Euler–Lagrange approach 159
- outer iterations, fluid-phase modeling 16–17
- p**
- parametric models 266–268
- partial vapor pressure, milk drying 177
- particle change rate 218
- particle collisions 181–192
–dry particles 189–190
–spray-dryer simulation 161
- particle displacement, balance equations 127
- particle morphology 201–203
- particle number, cell-average technique 219
- particle number concentration, spray-dryer simulation 197
- particle-phase properties, two way coupling procedure 173
- particle properties distributions 209
- particle relaxation time, particle collisions 182
- particle-size distribution
–computational fluid dynamics 158
–multidimensional population balances 255

- SIP *see* strongly implicit procedure
 size distribution 160
 size enlargement, product properties prediction 200
 skeletal frame of reference 130
 slip-rotation lift *see* Magnus force
 slip-shear lift *see* Saffman force
 smoothness sensor 15
 soaking wood samples 42
 software
 -dryer designs 301
 -dryers 263
 -drying 296–301
 -drying modeling 261
 softwood, drying behavior 25–29
 solid mass fraction, spray-drying process 185
 solid skeleton, thermohydromechanical drying 125–126
 solid velocity 104
 -averaged internal equations 112
 solids modeling difficulties 297–298
 solids processing challenge 262–263
 solids residence time 270
 solvent, mass flow rate 180
 solvent content, particle collisions 189
 solvent evaporation, particle morphology 202
 source terms, spray-dryer simulation 198
 spatial averaging theorem 3
 spatial deviation variables 5
 spatial discretization, spray dryer 192
 spherical volumetric strain tensor 114
 spray droplet 158
 spray-dryer geometry 192–193
 spray-dryer problems 282
 spray-dryer simulation 155–208
 -chamber design 160
 -collisions of particles 181–192
 -droplet-drying models 173–181
 -Euler–Lagrange approach 162–173
 -examples 192–200
 -prediction of product properties 200–203
 -state of the art 160–162
 stack model 43–51
 standalone calculation programs, dryers 263
 state equations, averaged internal 108
 STD droplets *see* surface-tension dominated droplets
 STD-STD collisions 190
 stochastic collision models 182–187
 Stokes number 184
 Stokesian drag force 191
 strain 116–118
 strain components, drying 141
 strain deviator 142
 strain rate tensor, balance equations 129
 strain tensor
 -averaged internal equations 110
 -drying quality 50
 -numerical resolution technique 114
 -rate equations 132
 streaming period, microwave heating 30
 stress deviator, thermohydromechanical drying 126
 stress profile inversion 115
 stress tensor
 -averaged internal equations 109
 -balance equations 128
 -constitutive equations 130
 strongly implicit procedure (SIP) 165
 structure influence, pore network models 57–102
 subcontrol volume (SCV) 12
 subgrid-scale models 156
 superficial averages, volume-averaging models 3
 superheated steam flow 25
 -high-temperature convective drying 19–22
 surface evaporation, heat transfer 91
 surface tension 141
 surface-tension dominated droplets (STD droplets) 161, 187–188, 190
 swelling strain 142
 symmetrical second-order stress tensor 109
- t**
 temperature distribution, microwave drying 150
 temperature evolution, convective drying 147
 temperature gradient, rate equations 133
 temperature patterns, computational fluid dynamics 283
 temperature pressure sensors 26
 temperature profile, identity drying card 33
 temperature two-dimensional predicted fields 116–118
 tensor evaluation
 -Arnoldi process 17
 -CV face 14–15

- tenors
 - deformation gradient 36
 - diffusion 14
 - diffusivity 6
 - effective stress 130
 - Eulerian correlation 172
 - gas permeability 6
 - liquid mobility 14
 - liquid permeability 6
 - mechanosorptive strain 50
 - mobility 15
 - permeability 6
 - Reynolds-stress 166
 - spherical volumetric strain 114
 - strain 50, 110, 114, 132
 - strain rate 129
 - stress 109–17, 128, 130
 - symmetrical second-order stress 109
 - total strain 110
 - viscoelastic strain 50, 110
 - viscous drag 6
 - viscous stress 110
- theorem
 - averaging 3, 5
 - gauss divergence 13
 - Gauss-Ostrogradsky 128
 - general transport 3
 - spatial averaging 3
- theory of mixtures,
 - thermohydromechanical drying 125–154
- thermal conduction 24
 - pore network models 88
- thermal equilibrium,
 - thermohydromechanical drying 126
- thermal shocks,
 - thermohydromechanical drying 125
- thermodynamic equilibrium,
 - constitutive equations 130
- thermodynamic fluxes, rate
 - equations 133
- thermohydromechanical drying
 - chemical potential 139
 - constant drying rate period 140
 - constituent velocity of moisture 126
 - constitutive equations 130–132
 - creep strain 134
 - deformations 125
 - dielectric properties 126
- thermohydromechanical model
 - continuous 125–154
 - global balance equations 126–130
 - heat and mass transfer 132–141
 - kaolin cylinder 144–152
 - skeletal frame of reference 130–132
 - thermomechanical equations 141–144
- thermomechanical models, continuous
 - 103–124
- thick films, pore networks 80
- thin films, pore networks 80
- throats
 - isothermal drying models 59
 - pore network models 57
 - refilling 73
 - saturation 62, 88
 - size distribution 67, 78
- time discretization
 - heat transfer 89
 - particle tracking 170
- time scale
 - fluid phase modeling 170–171
 - turbulence 182
- time step, isothermal drying models 65
- tissues, model calculation 42
- total gaseous pressure 10
- total momentum 143
- total momentum conservation 114
 - averaged internal equations 110
 - continuous thermomechanical drying 103
 - numerical resolution technique 114
- total strain tensor, averaged internal equations 110
- transfer coefficients, milk drying 177
- TransPore 17, 46
- transport equations 1–5
 - Euler–Lagrange approach 163
 - film flow 82
 - particle 277
 - phase source terms 164
- transport phenomena, volume-averaging models 1
- transport properties, identity drying card 33
- tree-search approach
 - decision making tools 289, 292–294
- troubleshooting
 - dryers 294
 - heat and mass balances 268
- turbulence modeling, approaches 157
- $\kappa-\epsilon$ turbulence models 157, 163
- turbulence scales, computational limits 156
- turbulence time scale, particle collisions 182
- turbulent dispersion modeling 171

- turbulent flows 155
- turbulent kinetic energy 166
- turbulent viscosity 157
- two-dimensional predicted fields 116–118
- two-equation models, turbulence 157
- two-fluid approach, Euler-Euler 158
- two-phase flows
 - Euler–Lagrange approach 159
 - stochastic collisions 182
- two-phase system, continuous
 - thermomechanical drying 107
- two-way coupling 173
 - fluid phase modeling 164
 - stack model 47
- two-zone process, drying phases 9

- u**
- underrelaxation procedure 173
- unit step function 218

- v**
- vacuum drying 10–11
- van der Waals forces 191
- van Leer flux limiter 15
- vapor
 - convective drying 145
 - enthalpy 113
 - rate equations 134
- vapor concentration, milk drying 177
- vapor condensation, heat transfer 89
- vapor diffusion 24
- vapor mass balance, stack model 46
- vapor phase, diffusivity 5
- vapor transfer 63–64
 - convective drying 145–146
 - isothermal drying models 58, 61
- vapor/liquid interface
 - convective drying 146, 148
- VD droplets *see* droplets dominated by viscous forces
- velocity, solid phase 104
- velocity, of the skeleton 126
- velocity field, Euler–Lagrange approach 163
- virtual mass force, Lagrangian particle tracking 168
- viscoelastic case, continuous thermomechanical drying 104
- viscoelastic material 142
- viscoelastic strain tensor
 - averaged internal equations 110
 - drying quality 50
- viscoelastic behavior 115–120
- viscosity 141
 - magnetic 136
 - pore network models 71
- viscosity change, VD collisions 190
- viscous drag tensor 6
- viscous droplets, particle collisions 161, 190–191
- viscous effects, length scales 75
- viscous forces 188
- viscous stress tensor 110
- volume-averaging models
 - comprehensive drying 1–52
 - continuous thermomechanical drying 103–124
 - convective drying 18–29
 - homogenization 37–42
 - less-common drying 29–37
 - macroscopic equations 6–7, 11–18
 - microscopic foundations 1–6
 - multiscale approach 42–51
 - physical phenomena 7–11
- volume conservation, averaged internal equations 108
- volume fraction, thermohydromechanical drying 126
- volumetric heating 29
- volumetric saturation 126
- volumetric strain 134
- von Mises stress 116–118

- w**
- wall deposition rates, spray-dryer simulation 160
- water, microwave heat source 138
- water activity, milk drying 177
- water conservation 13
 - volume-averaging models 6
- water content profiles 122
- water-vapor transport equations 1
- wave equation, microwave heat source 136
- wet porous medium 1
- wet solid, rheological behavior 103
- wettability effects 83–84
- wind-tunnel dryer 19
- wood variability 49–49

- y**
- y-periodic functions 40
- Ytong 19

Index

- 1D imaging, NMR 98
 2D imaging, NMR 98–99
 3D image filtering and segmentation, algorithms 157–163
 3D imaging, NMR 100–101
 90° scattered light detection 247
- a**
 absorbance image 80–81
 absorbance spectra, analysis 82
 absorption, total light, definition 76
 absorption bands
 – imaging apparatus 83
 – spectral analysis, soybean seeds 86–87
 – water and ice 83–85
 absorption spectrum, fresh melon 75
 acoustic attenuation spectroscopy 291
 acoustic field, characterization 42
 acoustic levitation 41–66
 – force, one-dimensional 46
 – interactions of a droplet with the sound pressure field 47–55
 – pure water droplets, evaporation rates 61–63
 – single droplet drying 55–66
 – solvent droplets, drying rate 58
 – standing acoustic waves 43–47
 acoustic levitator
 – typical 60–61
 – ventilation gas stream 52
 acoustic optical tunable filter (AOTF) 78
 acoustic streaming, primary and secondary 48–53
 acoustic wave, forces 43–47
 adhesion, particle 307–312
 adhesion force test methods 309–310
 adhesive interactions, wet granular media 254–255
 aerosol spectrometers, optical 243–244
- AFM *see* atomic force microscopy
 agricultural samples
 – MRI 125–137
 – transport phenomena 125–126
 Anated powder flow analyzer 346–348
 angle of repose, moving particle bed 329
 angular frequency, definition 42
 AOTF *see* acoustic optical tunable filter
 apparent absorbance, definition 76
 aqueous mannitol solution, single droplet drying 63–66
 aspect ratio
 – effect of droplet size 53
 – width/length 200
 aspect ratio method, sound pressure level 47
 asperity regime, capillary bridges 258
 atomic force microscopy (AFM), adhesion force measurement 310–312
 atomization air flow rates 234
 attenuation coefficients
 – X-ray 147–148, 158–163
 attrition coefficients, mass and surface-related 241–243
 attrition dust measurements
 – isokinetic sensor 237–243
 – on-line particle counter 243–250
 average moisture content, measurement 1–67
- b**
 backprojection algorithm, filtered 149–150
 balance, magnetic suspension *see* magnetic suspension balance
 bandpass filter, spectral information acquisition 78
 batch drying, fluidized beds 21–23
 beam-hardening, X-rays 152
 beam projections, X-ray image reconstruction 149–152

- bed dryer, continuous fluidized 25–27
 Beer-Lambert law, X-rays 145
 belt dryers, wastewater sludges 170–171
 BET *see* Brunauer-Emmett-Teller
 biaxial shear tester, Schwedes 344
 biological samples
 – NMR spectroscopy 126–128
 – transient moisture profiles 128–131
 bonding effects, particle surfaces 307–312
 boundary layer, sound pressure 50
 breakage, testing methods 320–321
 breakage probability, zeolite granules 324–325
 bridges, material 307–308
 Brunauer-Emmett-Teller model (BET-model)
 – surface area determination 298–300
 – *see also* gas adsorption method
 bubbles, optical particle detection 203
 bulk density, particle bed 328
 bulk solids
 – flow behavior 329–331
 Butt particle interaction apparatus 310–312
- c**
- calibration
 – infrared spectrometer 14–20
 – MRI 111–114
 calibration curves, NIR spectroscopy 82
 CAMSIZER 194–200
 capillary condensation 302–303
 capillary forces, between particles 256–258
 capillary state, wet granular media 261
 cardboard samples
 – calibration procedure 111–114
 – diffusion measurements 119–124
 – drying experiments and MRI
 parameters 109–111
 – drying profiles 114–119
 – moisture gradients 108–124
 CCD camera, CAMSIZER 195
 CD, cross-direction, cellulose fibers 103
 cellulose fibers 102–103
 cellulose samples, MRI, previous results
 104–105
 centrifugal method, adhesion force testing
 309–310
 chemical thermo mechanical pulp (CTMP)
 108
 chord length 282
 – particle 189
 circularity/sphericity, particle shape 200
 cluster volume distribution 164–165
 cohesive bulk solids, flow behavior 329–331
 cohesive interactions, wet granular media
 256–259
- cohesive powders, flow criteria 332–335
 colloid probe technique 310–312
 compressible bulk solids, flow behavior
 329–331
 compression test, particle breakage 321–325
 Compton scattering, X-rays 145
 concentrated suspension/slurry/dispersion
see sol concentration
see particle concentration
 condensation, capillary 302–303
 cone beam geometry, X-ray sources 155
 conical indentation, wet granular media 264
 consolidation and filtration expression
 characteristics 342
 constant-rate drying period 59
 constant time imaging (CTI) sequence,
 NMR 134
 constituent distribution, visualization 82
 constituent image, definition 82
 constitutive functions, particle properties 280
 contact drying
 – experimental set-up 176–177
 – spatio-temporal evolution 177–180
 contact preconsolidation 310
 Contin analysis 289
 continuous fluidized bed dryer, moisture
 distribution, modeling 25–27
 convective drying, sludges 167–173
 convexity, particle shape 200
 cotton fibers, water sorbed in 121
 Couette device, Tardos 346
 coulometry
 – advantages 32–33
 – and NMR, combination 37
 – moisture measurement 28–33
 critical stress intensity 267
 critical time, definition 26
 cross-correlation analysis, particle image
 velocimetry 209
 CTI *see* constant time imaging
 CTMP *see* chemical thermo mechanical pulp
 cumulant method, particle size
 distribution 279–280, 288–289
 cumulative number distribution, particle
 moisture 26–27
 cumulative pore volume plot 304
 cyclic stressing test, zeolite granules 323–324
 cylindrical hydrophilic particles, morphology of
 packing 179
- d**
- d^2 -law 56
 DCC *see* dynamic contamination control
 Debye plot 285

- deformation
 – droplet shape 48
 – testing methods 320–321
- DEM *see* discrete element method
- dense particle dispersions, ultrasonic methods 291–293
- desorption curves, SIC 8
- dew point measurement
 – experimental set-up 12
 – infrared spectrometer 13–14
 – infrared spectroscopy 10–24
 – particle systems 10–11
- dew point mirror 14–17
 – calibration device 16
- diametric compression, smooth spherical particles 253–254
- diffraction, laser light, particle dispersions 283–291
- diffuse reflection measurement 75
- diffusion coefficients 122–123
- diffusion measurements, MRI 119–124
- digital image analysis set-up 203
- dilute particle dispersions, laser light scattering and diffraction 283–291
- direct shear testing 266, 344–348
- discharge, particle stress 319
- discrete element method (DEM), simulation of rotating particles 351–352
- dispersions, solid-liquid 341
- DMT theory 255
- drop fluctuations, spectral analysis 218–223
- drop-out method, sound pressure level 47
- droplet drying kinetics, film theory 57
- droplet shape, deformation 48
- droplet size, effects of changing 53–55
- droplet surface, pressure difference across 53
- droplets
 – acoustic levitation 41–66
 – aqueous mannitol solution 63–66
 – drying rate, solutions or suspensions 58–59
 – interactions with the sound pressure field 47–55
 – mean moisture mass fraction 59
 – mean particle porosity 59
 – particle density 59
 – spherical solvent, drying rate 55–57
- dry powder, ring shear tester 339–340
- dry sample gas
 – volume 238
 – volume flow rate 237
- drying air
 – flow rates 62
 – temperature 65
- drying curves, MRI 91–137
- drying drum, particle rotation 319
- drying front, spatio-temporal evolution 177–180
- drying kinetics
 – film theory 57
 – measurement 1–67
 – single particle 2–4, 20–24
- drying optimization, xerogels 173–175
- drying profiles, cardboard samples 114–119
- drying rate
 – acoustically levitated solvent droplet 58
 – droplets of solutions or suspensions 58–59
 – first period 39
 – normalized 25
 – spherical solvent droplet 55–57
- Dubinin-Radushkevich method 301–302
- dust mass flow rate 249–250
- dynamic contamination control (DCC), dew point measurement 15
- e**
- effective amplitude, definition 45–46
- elastic impact 313–318
- elastohydrodynamic lubrication 260
- elastoplastic measurements, wet granular media 262–266
- electrokinetic sonic amplitude (ESA) spectroscopy 292–293
- electrolysis current, moisture distribution 30–32
- electrolytic cell, coulometry 29
- electromagnetic spectrum 145
- electron microscopy, particle size distribution 281
- Enstad uniaxial tester 344–346
- equilibrium moisture content 39
- ESA *see* electrokinetic sonic amplitude
- evaporation rate 11, 17
 – acoustically-levitated pure water droplets 61–63
 – aqueous mannitol solution droplets 63–66
- extrudates, sludge 167–170
- f**
- failure properties, wet granular media 266–269
- falling-rate drying period 59
- fan beam geometry, X-ray sources 155
- fan beam projections 151–152
- Feldkamp algorithm 152
- Feret chord length 282
- fiber optical probe measurement technique
 – calibration 231–232

- particle concentration and velocity 203, 228–236
 - results 232–236
 - fiber saturation point (FSP) 103
 - fibers
 - cellulose 102–103
 - pore sizes within 121
 - FID *see* free induction decay
 - field of view (FOV) 205
 - film theory, droplet drying kinetics 57
 - filtered backprojection algorithm 149–150
 - filtration and consolidation expression characteristics 342
 - fine particles, physical properties 279–283
 - first period drying rate 39
 - fitting algorithms, sieve correlation 198–200
 - flow behavior, bulk solids 329–331
 - flow criteria, preconsolidated cohesive powders 332–335
 - flow diagram, particle image velocimetry 212
 - flow rates
 - atomization air 234
 - drying air 62
 - dust 249–250
 - fluidized beds
 - attrition measurement 237–243
 - batch drying 21–23
 - continuous drying 25–27
 - dew point measurement 11
 - experimental set-up 12
 - granulation 319
 - parameters of drying experiments 21
 - particle stability 236–250
 - porosity 232–233
 - spray granulation 190–194
 - food samples
 - moisture distribution 73–88
 - MRI 125–137
 - NMR spectroscopy 126–128
 - transient moisture profiles 128–131
 - transport phenomena 125–126
 - force-displacement behavior, zeolite granules 321–323
 - force-separation measurement 310–312
 - forces
 - adhesion 308–309
 - capillary 256–258
 - in a standing acoustic wave 43–47
 - interparticle 252–261
 - FOV *see* field of view
 - fracture, granular materials 267–268
 - Fraunhofer range 244
 - Fraunhofer theory 284, 289–290
 - free-fall device, impact measurement 315–316
 - free induction decay (FID) 96
 - frequency, sound pressure wave 43–44
 - frequency encoding, NMR 98
 - frictional force, Hertzian particles 259
 - frictional interactions, wet granular media 259–261
 - FSP *see* fiber saturation point
 - fully and partially saturated wet granular media, mechanical properties 251–269
 - funicular state, wet granular media 261
- g**
- $\gamma\text{-Al}_2\text{O}_3$
 - desorption curves 7–8
 - pore diameter 6
 - γ -ray attenuation methods, moisture profiles 91
 - gas adsorption method 280
 - pore size distribution 300–307
 - specific surface area 296–300
 - *see also* Brunauer-Emmett-Teller model
 - gas particle displacement, definition 42
 - gas particle velocity, definition 42
 - gas-phase pressure fluctuations, spectral analysis 221–222
 - gas pycnometry 294–295
 - GE *see* gradient-echo
 - gels, moisture profiles 130–131
 - geometrical range *see* Fraunhofer range
 - Glycine max, moisture distribution 85
 - gradient-echo (GE) sequence, NMR 102
 - granular materials
 - fracture 267–268
 - underconsolidated 262
 - granulation, in fluidized bed 319
 - grating, spectral information acquisition 78
- h**
- Hahn-echo NMR pulse sequences 126–127
 - half-value layer (HVL) 145
 - Hamaker constant 333
 - HE-pycnometry 293–295
 - Helmholtz equation 46
 - Herschel-Bulkley parameters 265
 - Hertzian particles, frictional force 259
 - high-speed camera, particle bed movement 348–352
 - HVL *see* half-value layer (HVL)
 - hydrodynamic method, adhesion force testing 310
 - hydrodynamic stability *see* particle stability
 - hyperspectra

- soybean seeds 86
- water and ice 84
- hyperspectrum**
 - image processing 79
 - near-infrared spectral imaging 76–77
- i**
- ice**
 - absorption bands 83–85
 - hyperspectra 84
 - shear testing technique SSTT 337–339
- illumination, spatial correction** 204–205
- image acquisition**
 - particle image velocimetry 208
 - spatial information acquisition 79
- image analysis**
 - by optical and scanning electron microscopy 280–283
 - set-up, digital 203
- image filtering and segmentation, algorithms** 157–163
- image processing** 79–82
 - acquisition and pretreatment of spectral data 81–82
 - analysis of absorbance spectra 82
 - conversion into absorbance image 80–81
 - hyperspectrum 79
 - noise and shading correction 79–80
 - visualization of constituent distribution 82
 - X-ray tomography 157–166
- image reconstruction, X-ray tomography** 148–153
- imaging apparatus, water and ice absorption bands** 83
- imaging principles, NMR** 97–101
 - 1D imaging 98
 - 2D imaging 98–99
 - 3D imaging 100–101
 - slice selection 99–100
- imaging sequences, NMR** 101–102
- impact, between solid bodies** 313–318
- impact separation method, adhesion force testing** 310
- impact test, particle breakage** 325–328
- in-line particle size measurement** 188–194
 - batch granulation of pharmaceutical products 191–194
 - continuous granulation of detergents 190–191
 - instrumentation 189
- indicator Kriging algorithm** 162–163
- indirect shear testers** 344–348
- industrial tomography** 155–156
- information acquisition techniques** 77–79
- infrared (IR) spectrometer**
 - calibration 14–17
 - linearization 17
 - testing the calibration 10–24
- infrared (IR) spectroscopy, dew point measurement** 10–24
- Institution of Chemical Engineers (ICE), shear testing technique** 337–338
- integral moisture balance** 19–20
- inter-fiber pores, paper** 103
- interface curvature, liquid-vapor interface** 166
- interfacial area, liquid-vapor interface** 166
- interparticle forces, wet granular media** 252–261
- interrogation areas, particle image velocimetry** 209
- intra-fiber pores, paper** 103
- invasive methods, moisture profiles** 91
- ipp-70 probe** 190
- IR** *see* infrared
- isokinetic sensor, attrition dust measurements** 237–243
- j**
- Jenike translational shear cell** 335–339
- JKR theory** 255
- k**
- Kelvin equation** 258
- King's equation** 43
- Kriging algorithm** 162–163
- l**
- Lambert-Beer law** 74–76
- Laplace-Young equation** 257
- large-scale X-ray tomography** 155–156
- Larmor relation** 94
- laser light scattering and diffraction, dilute particle dispersions** 283–291
- lateral force microscopy (LFM)** 261
- LCTF** *see* liquid crystal tunable filter
- levitation, acoustic** *see* acoustic levitation
- LFM** *see* lateral force microscopy
- light scattering and diffraction, dilute particle dispersions** 283–291
- line integral concept, X-ray image reconstruction** 148–149
- line scanning, spatial information acquisition** 79
- linear attenuation coefficient, X-rays** 146
- linearization, IR spectrometer** 17–18
- liquid crystal tunable filter (LCTF)** 78
- liquid self-diffusivities** 123–124

- longitudinal relaxation time 95–97
 Lorentz-Mie theory 243–244
 low-resolution NMR spectroscopy 126–127
 lubrication, elastohydrodynamic 260
 lubrication interactions, wet granular media 259–261
- m**
- macrotomography, X-ray 155–156
 magnetic resonance imaging (MRI)
 – calibration procedure 111–114
 – conversion of signal to water content 135
 – diffusion measurements 119–124
 – drying of agricultural and food samples 125–137
 – drying of paper, pulp and wood samples 102–124
 – general data 102–104
 – moisture profiles and drying curves 91–137
 – net magnetization 94–95
 – paddy rice kernels 132–137
 – parameters and drying experiments 109–111
 – principles 93–102
 magnetic suspension balance (MSB) 2–10
 – configuration and periphery 4–6
 – experimental results 6–10
 – experimental set-up 5
 – single particle drying kinetics 2–4
 Martin chord length 282
 mass attenuation coefficient, X-rays 147–148
 mass flow rate, dust 249–250
 mass-related attrition coefficients 241–243
 material bridges, between particle surfaces 307–308
 maximum chord length 282
 MD, machine direction, cellulose fibers 103
 mean moisture mass fraction, droplets 59
 mean particle porosity, droplets 59
 mean residence time, definition 26
 measuring volume, small optical 244–246
 mechanical interactions, wet granular media 252–254
 mechanical stability, particles 236–250
 melon, absorption spectrum 75
 mesoporosity, measurement 302–304
 microbalance *see* magnetic suspension balance
 microporosity, measurement 301–302
 microslicer 83
 microtomography, X-ray 156–157
 Mie range 244
 mixed lubrication 260
 moisture
 – quantitative analysis, procedure 30
 – *see also* water
 moisture balance, integral 19–20
 moisture content
 – and volume concentration 14
 – change 11
 – equilibrium 39
 – measurement for justification of linearization 17
 moisture distribution
 – at the outlet of a continuous fluidized bed dryer 25–27
 – experimental 37–41
 – food, near-infrared spectral imaging 73–88
 – particle systems 24
 – soybean seeds 85–88
 – visualization 83–88
 moisture gradients, in cardboard samples 108–124
 moisture profiles
 – γ -ray attenuation methods 91
 – in a gel 130–131
 – invasive and non-invasive methods 91
 – MRI 91–137
 – paddy rice kernels, non-intrusive measurements 132–137
 – transient, food and biological samples 128–131
 mollified phase function 165
 morphological characteristics, X-ray
 – attenuation coefficients 163–167
 morphology of packing
 – cylindrical hydrophilic particles 179
 – spherical hydrophilic particles 178
 moving particle bed, angle of repose 329
 MRI *see* magnetic resonance imaging
 MRI signal
 – and moisture profiles 135–137
 – conversion to water content 135
 MSB *see* magnetic suspension balance
 multiexponential sampling analysis 289
 multiple detectors, spatial information acquisition 79
- n**
- nanoparticles, physical properties 279–283
 near-infrared (NIR) spectral imaging 74–79
 – hyperspectrum 76–77
 – Lambert-Beer law 74–76
 – moisture distribution in foods 73–88
 – spatial information acquisition technique 78–79
 – spectral information acquisition technique 77–78
 – spectroscopy 74

- visualization of moisture distribution 83–88
 - near-infrared (NIR) spectroscopy 74
 - calibration curves 82
 - second derivative spectrum 81
 - NIR camera 83
 - NMR
 - and coulometry, combination 37
 - basic 94–97
 - NMR spectroscopy
 - biological and food products 126–128
 - low-resolution 126–127
 - moisture measurement 33–37
 - rice kernels 132–134
 - noise correction, image processing 79–80
 - non-intrusive measurements
 - moisture profiles in paddy rice kernels 132–137
 - NMR preliminary experiments 132–134
 - particle concentration measurements 201–208
 - non-invasive methods, moisture profiles 91
 - normalized drying rate, single particle 25
 - normally consolidated media, granular 261
 - nuclear magnetic moment 94
 - nuclear magnetic resonance *see* NMR
 - Nusselt number, thin film 57
- o**
- OAS *see* optical aerosol spectrometers
 - off-line particle size measurement 194–200
 - detection of particles 195
 - outline of particles 195–196
 - shape 200
 - sieve correlation and fitting 198–200
 - on-line particle counter, attrition dust and overspray measurements 243–250
 - one-dimensional acoustic levitation force 46
 - optical aerosol spectrometers (OAS) 243–244
 - optical microscopy, particle size distribution 281–283
 - optical particle detection 202–208
 - bubbles 203
 - digital image analysis set-up 203
 - field of view 205
 - illumination 204–205
 - solids fraction 205–206
 - *see also* fiber optical probe measurement technique
 - optical volume limitation 247
 - overconsolidated media, granular 261
 - overspray measurements, with an on-line particle counter 243–250

p

- packed beds
 - contact drying 176–180
 - dew point measurement 11
 - sludge 170–173
- paddy rice kernels, MRI 132–137
- paper, porosity scales 103
- paper samples, MRI
 - general data 102–104
 - previous results 104–105
- parallel beam geometry, X-ray sources 155
- PARSUM probe 189
- partially and fully saturated wet granular media, mechanical properties 251–269
- particle abrasion, measurement 318–328
- particle adhesion 254–255
 - adhesion force test methods 309–310
 - comparison of adhesion forces 308–309
 - measurement 307–312
- particle bed movement, in rotary drums 348–352
- particle bed properties 328–348
 - angle of repose 329
 - bulk density and tapping density 328
 - cohesive and compressible bulk solids 329–331
 - direct and indirect shear testers 344–348
 - physical 279–283
 - preconsolidated cohesive powders 332–335
 - press shear cell 340–344
 - ring shear tester 339–340
 - translational shear cell 335–339
- particle breakage
 - measurement 318–328
 - testing methods 320–321
- particle chord lengths 189
- particle circulation time 224–228
- particle concentration
 - fiber optical probe measurement technique 203, 228–236
 - non-intrusive measurements 201–207
- particle deformation, testing methods 320–321
- particle density, droplets 59
- particle detection
 - off-line measurement 195
 - optical 202–207
- particle dispersions
 - laser light scattering and diffraction 283–291
 - ultrasonic methods 291–293
- particle drying kinetics, comparison of measurement methods 3
- particle edge

- correction according to iso 196
- determination 195
- particle flow rate variation, parameters 38
- particle formation, aqueous mannitol solution droplets 63–66
- particle formulation processes, measuring techniques 187–270
- particle image velocimetry (PIV) 201, 208–218
 - cross-correlation analysis 209
 - flow diagram 212
 - image acquisition 208
 - interrogation areas 209
 - velocity vector maps 212–215
- particle interaction apparatus, Butt 310–312
- particle moisture
 - as a distributed property 24
 - cumulative number distribution 26–27
- particle outline, off-line measurement 195–196
- particle properties, physical *see* physical particle properties
- particle restitution coefficient, measurement 312–318
- particle shape
 - definition 283
 - off-line measurement 200
 - parameters 200
- particle size
 - measurement 188–200
 - parameters 197
 - volume-related 198
 - *see also* in-line particle size measurement; off-line particle size measurement
- particle size distribution
 - analysis 280–293
 - cumulative 279–280, 288–289
 - density 248
 - sum 248
- particle stability
 - during fluidized bed processing 236–250
 - hydrodynamic 218–223
- particle stresses 319
- particle surfaces, bonding effects 307–312
- particle systems, dew point measurement 10–11
- particle tracking, positron emission 223–228
- particle velocity 208–218
 - fiber optical probe measurement technique 228–236
- particles
 - acoustic levitation 41–66
 - fine 279–283
 - gas 42
- Hertzian 259
- morphology of packing 178–179
- rotating 351–352
- single *see* single particle drying
- spherical *see* spherical particles
- stiff, with soft contacts 333
- pastes *see* soft solids
- PCS-2010, measuring principle 248
- pendular state, wet granular media 261
- pendulum experiments, impact measurement 316–317
- PEPT *see* positron emission particle tracking
- percolation 165
- PFG *see* pulsed field gradient (PFG) NMR
- PGSE, pulsed gradient spin-echo
- phase encoding, NMR 99
- phase segmentation, X-ray tomography 163–167
- phase volume fraction 164
- photoelectric absorption, X-rays 144–145
- physical particle properties 279–352
 - measurement 293–328
 - mesoporosity 302–304
 - microporosity 301–302
 - particle abrasion and breakage 318–328
 - particle adhesion 307–312
 - particle bed *see* particle bed properties
 - particle restitution coefficient 312–318
 - pore size distribution 300–307
 - pore volume 304–305
 - solid density analysis 293–295
 - specific surface area 296–300
 - volume determination 294–295
- PIV *see* particle image velocimetry
- plastic zone, fracture of granular materials 267
- platinum resistance thermometer (PRT) 15
- Polanyi theory 301
- pore size distribution
 - gas adsorption method 300–307
 - measurement set-up 305–307
- pore sizes, within fibers 121
- pore volume, measurement 304–305
- pore volume plot, cumulative 304
- porosity
 - fluidized bed 232–233
 - mean particle 59
 - paper 103
- positron emission particle tracking (PEPT) 202, 223–228
- powder flow analyzer, Shearscan TS12 346–348
- powders
 - classification 331

- cohesive 332–335
- single particle drying kinetics 20–24
- preconsolidated cohesive powders, flow criteria 332–335
- press shear cell, Reichmann 340–344
- pressure difference, across droplet surface 53
- pressure drop fluctuations
 - spectral analysis 202, 218–223
- pressure nodes, effect of droplet size 54–55
- primary acoustic streaming 48–53
- process zone *see* plastic zone
- projections
 - fan beam 151–152
 - X-ray image reconstruction 149–152
- PRT *see* platinum resistance thermometer
- pulp samples, self-diffusivity 123–124
- pulsed field gradient (PFG) NMR 127
- pulsed gradient spin-echo (PGSE)
 - technique 119–124
- pure water droplets, acoustically-levitated 61–63
- pushbroom method, spatial information acquisition 79

- q**
- quasi-elastic light scattering (QELS) 286–287

- r**
- radio frequency excitation, MRI 94–95
- Radon transform 149–150
- ram extrusion 265
- rate constant, definition 26, 40
- Rayleigh-Debye equation 285
- Rayleigh-Gans-Debye theory 284
- Rayleigh range 244
- Rayleigh theory 284
- refraction, Snell's law 228–229
- regions of interest (ROIs), spectral information acquisition 81, 84, 86
- Reichmann press shear cell 340–344
- relaxation, and NMR signal 95–97
- repose angle, moving particle bed 329
- resorcinol-formaldehyde xerogels, drying optimization 173–175
- rice kernels, moisture profiles 132–137
- ring shear tester, Schulze 339–340
- ROI *see* regions of interest
- rotary drums, particle bed movement 348–352
- rotating particles, discrete element method 351–352
- roughness regime, capillary bridges 258
- Ruiz-Cabrera method 130–131

- s**
- SAPDF *see* spectral analysis of pressure drop fluctuations
- scanning electron microscopy (SEM), particle size distribution 281–283
- scattered light detection, 90° 247
- scattering, laser light, particle dispersions 283–291
- Schulze ring shear tester 339–340
- Schwedes biaxial shear tester 344
- SE *see* spin-echo
- second derivative spectrum
 - NIR spectroscopy 81
 - soybean seeds 87–88
- secondary acoustic streaming 48–53
- segmentation algorithms, X-ray attenuation 161–162
- self-diffusivity, pulp samples 123–124
- shading correction, image processing 79–80
- shear cell
 - Jenike translational 335–339
 - Reichmann 340–344
- shear force-displacement curves 338
- shear testers
 - direct and indirect 344–348
 - Schulze 339–340
 - survey 348
- shear testing technique SSTT 337–339
- Shearscan TS12 346–347
- Sherwood number 51
- SIC
 - desorption curves 8
 - pore diameter 6
- sieve analysis, off-line particle size measurement 198–200
- signal intensity, MRI in cardboard samples 111
- simulation of rotating particles, discrete element method 351–352
- single droplet drying
 - aqueous mannitol solution 63–66
 - drying rate 55–57
 - water 59–63
- single particle drying
 - general remarks 2–4
 - normalized drying rate 25
 - powdery material 20–24
- single point detectors, spatial information acquisition 79
- sinogram *see* Radon transform
- slice selection, NMR 99–100
- sludges
 - convective drying 167–173
 - individual extrudates 167–170

- packed bed 170–173
 - slump test 251–252
 - slurry state, wet granular media 261
 - small droplets, acoustic levitation 41–66
 - small optical measuring volume 244–246
 - Snell's law 228–229
 - sodium benzoate granules 319
 - sol 251
 - solid bodies, impact 313–318
 - solid density analysis, HE-pycnometry 293–295
 - solid-liquid dispersions, flow
 - characteristics 341
 - solids
 - soft 251
 - wet granular 251
 - solids fraction, stagnant bed 205–206
 - solvent droplets
 - acoustically levitated, drying rate 58
 - spherical, drying rate 55–57
 - sound pressure
 - definition 42
 - infinite levitator 45
 - sound pressure boundary layer 50
 - sound pressure field
 - change of droplet size 53–55
 - deformation of droplet shape 48
 - interactions with droplets 47–55
 - primary acoustic streaming 48–53
 - sound pressure level (SPL)
 - definition 42
 - effect of droplet size 54
 - effective 47
 - sound pressure wave, frequency 43–44
 - sound velocity level (SVL), definition 42
 - soybean seeds 86–87
 - moisture distribution 85–88
 - second derivative spectrum 87–88
 - Spalding transfer number 57
 - spatial filtering velocimetry 188–189
 - spatial information acquisition
 - technique 78–79
 - spatio-temporal evolution, contact
 - drying 177–180
 - specific surface area
 - BET-model 298–300
 - gas adsorption method 296–300
 - spectral analysis
 - absorption bands
 - of pressure drop fluctuations (SAPDF) 202, 218–223
 - spectral data
 - acquisition 81–82
 - pretreatment 81–82
 - spectral illuminator 83
 - spectral imaging, near-infrared *see* near-infrared spectral imaging
 - spectral information acquisition technique 77–78
 - sphere indentation, wet granular media 263
 - spherical particles
 - capillary forces 256–258
 - diametric compression 253–254
 - morphology of packing 178
 - Young's modulus 253
 - spherical regime, capillary bridges 258
 - spherical solvent droplets, drying rate 55–57
 - sphericity/circularity, particle shape 200
 - spin-echo (SE) sequence, NMR 101–102
 - spin-lattice relaxation *see* longitudinal relaxation time
 - spin-spin relaxation *see* transverse relaxation time
 - SPL *see* sound pressure level
 - spout-fluid bed
 - particle circulation time 227–228
 - spectral analysis 219
 - spraying rate 17–18
 - spring balance method, adhesion force testing 309–310
 - squeeze flow, wet granular media 265
 - SSTT, shear testing technique 337–338
 - stagnant bed, solids fraction 205–206
 - standing acoustic wave, forces 43–47
 - Stefan flow 57
 - stiff particles with soft contacts, model 333
 - strain energy release rate 268
 - surface area
 - BET-model 298–300
 - gas adsorption method 296–300
 - surface-related attrition coefficients 241–243
 - surfaces
 - bonding effects 307–312
 - pressure difference across 53
 - SVL *see* sound velocity level
 - symmetry, particle shape 200
 - synchrotron X-ray microtomography 157
- t**
- tapping density, particle bed 328
 - Tardos Couette device 346
 - temperature, drying air 65
 - temperature protocols, moisture distribution 30–32
 - tension tests 268
 - test methods
 - adhesion force 309–310

- breakage 320–321
- pore size distribution 305–307
- thin films, Sherwood number 57
- thin layer method (TLM), packed beds 11
- three-point bend method 267
- time-domain NMR *see* low-resolution NMR spectroscopy
- TLM *see* thin layer method
- total amount of water, MRI calibration 113
- total light absorption, definition 76
- transient moisture profiles, food and biological samples 128–131
- translational shear cell, Jenike 335–339
- transport phenomena, agricultural and food products 125–126
- transportation, particle stress 319
- transverse relaxation time 96–97
- triaxial tests 267
- Trouton ratio 265
- tunable filter, spectral information acquisition 78

- u**
- ultrasonic levitation *see* acoustic levitation
- ultrasonic methods, dense particle dispersions 291–293
- unassigned voxels, X-ray attenuation 163
- underconsolidated media, granular 262
- uniaxial tester, Enstad 344–346

- v**
- van der Waals forces 309
- velocimetry
 - particle image *see* particle image velocimetry
 - spatial filtering 188–189
- velocity *see* particle velocity
- velocity vector maps 212–215
- ventilation gas stream, acoustic levitator 52
- vibration method, adhesion force testing 310
- viscous force 258
- visualization
 - constituent distribution 82
 - moisture distribution 83–88
- volume concentration, and moisture content 14
- volume determination, using gas pycnometry 294–295

- w**
- wastewater sludges *see* sludges
- water
 - absorption bands 83–85
 - hyperspectra 84
 - single droplet drying 59–63
 - sorbed in cotton fibers 121
- water concentration profiles, MRI calibration 112–113
- water content
 - conversion of NMR signal 135
 - *see also* moisture
- water droplets, acoustically-levitated 61–63
- web, cellulose fibers 103
- wet filter cake, press shear cell 340–344
- wet granular media
 - adhesive interactions 254–255
 - cohesive interactions 256–259
 - elastoplastic measurements 262–266
 - failure properties 266–269
 - frictional and lubrication interactions 259–261
 - interparticle forces 252–261
 - mechanical interactions 252–254
 - mechanical properties 251–269
- wet granular solids 251
- wet sample gas
 - particle concentration 240
 - velocity 239–240
 - volume 239
- width/length aspect ratio, particle shape 200
- wire cutting 268
- wood samples, MRI, general data 102–104

- x**
- X-ray attenuation coefficients 147–148, 158–163
- morphological characteristics 163–167
- X-ray macrotomography 155–156
- X-ray microtomography 156–157
- synchrotron 157
- X-ray sources, geometry 154–155
- X-ray tomography 143–181
 - applications 167–180
 - fundamentals and principles 143–153
 - geometry of CT systems 153–155
 - image processing 157–166
 - image reconstruction 148–153
 - instrumentation 153–157
 - large-scale 155–156
 - packed bed, contact drying 176–180
 - physical principles 144–148
 - resorcinol-formaldehyde xerogels, drying optimization 173–175
 - sludge, convective drying 167–173
- x-y scanning, spatial information acquisition 79
- xerogels, drying optimization 173–175

y

Young's modulus, smooth spherical particles 253

z

ZD, *z*-direction, cellulose fibers 103

zeolite 4A

– adsorption 9

– desorption curves 7–8

– mass determination 10

– pore diameter 6

zeolite granules

– breakage probability 324–325

– cyclic stressing test 323–324

– force-displacement behavior 321–323

Zimm plot 285–286

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 syrup 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
 - $\gamma\text{-Al}_2\text{O}_3$ 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**
 $\gamma\text{-Al}_2\text{O}_3$ agglomerates
– breakage probability 315
– fracture surface 316–317
 $\gamma\text{-Al}_2\text{O}_3$ 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
gelatinization, 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
- hygrosensitivity 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 funtion, 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
- Si_3N_4 -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
- SMARTTM 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**
 - gelatinization 245
 - mint oil particle size 360
 - orange oil particle size 360
 - bergamot 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 Si(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
 - vaccuum drying 198
- y**
- Young's modulus
 - rice grains 35
 - time-dependent 36
- z**
- zeolite agglomerates 317–319

Index

a

- absorber arrangements, flat plate
 - collectors 205
- absorber materials, properties of 208
- absorption refrigeration cycle, HPD 139–140
- active pharmaceutical ingredients (API),
 - drying by HPD 152–153
- adsorption drying. *see also* zeolites
 - adsorption wheel *versus* packed bed 181–182
 - air dehumidification 170–173
 - defining energy efficiency 173–174
 - direct contact drying 169–170
 - dryer systems for zeolite 180–181
 - energy efficiency and heat recovery 173–180
 - energy recovery for single-stage systems 174–176
 - energy recovery in multi-stage systems 176–178
 - energy recovery with superheated steam 178–180
 - realization of dryer systems 180–185
 - types of drying systems 168–169
- adsorption heat, zeolites 165
- adsorption isotherms 166–167
 - data for zeolites 195–196
- adsorption materials
 - comparing zeolites and other adsorbents 166–168
 - zeolites 164–168
- adsorption wheel systems 183–185
 - *versus* packed bed 181–182
- AFD. *see* atmospheric freeze drying
- agglomeration, in separation processes 92–93
- agricultural products, applications of HPD 150–152

- air cycle, psychrometric chart 128
- air dehumidification
 - flows in dryers 171–172
 - zeolites 168–173
- air recirculation, solar dryers 232
- air renewal, and energy consumption 264–265
- air-tightness, and energy consumption 268
- airflow
 - convective dryer 28
 - in flat plate collectors 205
- airflow management, solar dryers 231–232
- ambient air, moisture content of 172
- annuity, solar drying 235
- API. *see* active pharmaceutical ingredients
- Appropriate Placement principle, applied to dryers 21–25
- apricots, solar drying of 230–231
- aromatic plants, solar drying of 211, 217–219, 227–228
- ASHRAE standard (ANSI/ASHRAE, 1986),
 - solar air heaters 206
- atmospheric carbon dioxide 245–246
- atmospheric freeze drying (AFD), using HPD 149–150
- Azurara's model, osmotic dehydration 104–105

b

- back-up heating systems, solar dryers 232–234
- bacterial flocs, sludge 297–298
- balm, drying characteristics of 228
- bark, energy yield 283
- bast fiber
 - anatomical structure of 252
 - chemical composition of 249
 - dimensions of fibers from 253

- beam radiation, solar 202–203
- belt dryers, for sludge 302–303, 306
- biofuels
 - drying as precondition 271–281
 - heat treatment as precondition 281–287
 - production of 246–247
- biological products, drying by HPD 152–153
- biomass. *see also* renewable material; wood
 - conveyor dryers for 273–274
 - fixed bed dryers for 275–276
 - fixed carbon content of 249
 - fluidized bed dryers for 275
 - rotary dryers for 274–275
 - as a source of renewable material and energy 245–254
 - thermochemical conversion of 272
 - volatile matter of 249
- biomass drying
 - energy issues 245–287
 - global model 278–281
 - local model 276–278
 - numerical approach 276–281
 - precondition for energy production 271–281
- biomass heat treatment
 - modeling of 284–287
 - precondition for energy production 281–287
- biomass to liquid (BTL) process 248
- blanching, dehydration pretreatment 101
- blocking filtration 72–73
- body feed filtration 93–94
 - principle 80
- boiler efficiency 8
- boiler feedwater heating 8–9
- box kiln, vertical cross-section through 259
- Brazil
 - drying of timber in 235–237
 - drying of tobacco in 237–239
- c**
- cabinet dryers, solar 213–214
- cake filtration 61–72
- calorific value, of lignocellulosic materials 251
- cane
 - anatomical structure of 252
 - chemical and energy properties of 250
 - chemical composition of 249
 - dimensions of fibers from 253
- capillary pressure, filter pore 63–64
- carbon dioxide emissions 245–246
 - and carbon footprint 15–16
- cascade heat pumps 133–135
- cellulose, as component of lignocellulosic materials 247–249
- centrifugal cake filtration 66–69
 - principle of 67
- centrifuges, for sedimentation 57–61
- CFCs. *see* chlorofluorocarbons
- chamber filter press 70
- chamomile
 - drying characteristics of 228
 - solar drying of 230–231
- chemical heat pumps (CHP) 135–138
 - concept of 136
 - scheme of proposed system 137
- chlorofluorocarbons (CFCs), refrigerants 125–126
- CHP. *see* chemical heat pumps; combined heat and power
- clarification, of liquids 48
- clarification area, sedimentation basins 56
- coating, dehydration pretreatment 102
- coefficient of performance (COP)
 - absorption refrigeration cycle 140
 - heat pumps 125, 129, 132–133
- cold streams, in dryers 18, 20
- collectors. *see also* solar collectors; solar dryers
 - special surfactants 52
- combination osmotic drying 107–108, 111–112
- combined heat and power (CHP)
 - for energy reduction 24, 34–36
 - and utility systems 42–43
- composite curves. *see also* grand composite curves
 - convective steam-heated dryers 19
 - food processing 39–40
 - for gelatin process 23–24
 - liquid-phase processes 18
- computational models. *see also* modeling
 - of biomass drying 276–281
- concentration, of suspensions 48
- continuous drying models
 - global model 278–281
 - local model 276–278
- convection
 - forced 214–223
 - natural 212–214
- convective drying
 - reducing heater duty 28
 - of sludge 301–305
- convective steam-heated dryers
 - breakdown of fuel use 10
 - composite curves 19
 - GCC 20–21
- conventional drying. *see also* kiln-drying

- drying time and energy efficiency 259–262
 - of wood 258–262
 - conveyor dryers
 - for biomass 273–274
 - counter- and parallel-flow configuration 280–281
 - wood chips in 279
 - COP. *see* coefficient of performance
 - costs. *see also* economic aspects; energy costs
 - counter-flow configuration, conveyor dryers 280–281
 - cover materials, solar collectors 209
 - cross separation arrangement 91–92
 - crossflow filtration 73–75
- d**
- dairy industry, zeolite-assisted drying 185–189
 - Darcy's law, filtration 62
 - decanter centrifuges 59
 - dehumidification
 - of solids 48
 - of wood 270
 - dehumidified air, drying with 168–173
 - density separation processes
 - froth flotation 51–54
 - sedimentation 54–61
 - depth filtration 75–80
 - particle deposition in 77
 - diaphragm filter press 70
 - differential heat, of sorption 263
 - direct contact drying
 - manure and sludge 189–190
 - seeds 191–193
 - zeolites 168–170, 189–193
 - direct-fired dryers 11–13
 - direct solar drying
 - definition 211
 - with natural convection 212–213
 - disc dryers
 - evaporation performance 309
 - rotor design 306–308
 - disc filters 65–66
 - disc stack separators 60
 - double belt press filter 71
 - drum dryers, for sludge 304–306
 - drum filters 65–66
 - drum system, seed drying 191
 - dryer body, heat losses 7–8
 - dryer efficiency
 - improvement by altering operating conditions 30
 - and thermal valorization 321–322
 - dryer options, for energy reduction 37–38
 - dryer scale model, of biomass drying 278–281
 - dryers. *see also* drying; specific types
 - application of pinch analysis 19–21
 - for biomass 273–276
 - cold streams 18, 20
 - direct-fired 11–13
 - electrically heated 12–13
 - energy analysis of 1–43
 - energy consumption 38–42
 - energy supply 4–5
 - fundamentals of energy usage 3–16
 - heat exchange 31
 - heat-pump 127–129
 - hot streams 17–18, 20
 - primary energy use 14
 - rotor design 306–308
 - spray 38, 41
 - steam-heated 8–11
 - thermal inefficiencies 6–8
 - vacuum band 37, 41
 - vacuum tray 37, 41
 - drying. *see also* dryers
 - atmospheric freeze drying 149–150
 - computational models of 276–281
 - with dehumidified air 168–173
 - direct-contact 168–170
 - heat pump assisted spray drying 147–148
 - HPD (*see* heat pump drying)
 - industrial 2–3
 - and insoluble or soluble solids 25–26
 - osmo-convective 107–109
 - osmo-freeze 109–111
 - osmotic-vacuum 113–114
 - and overall process 25–26
 - projects with zeolites 185–193
 - reducing inherent heat requirement 29–30
 - solid wood and other biomass sources 245–287
 - of timber 150–152
 - time-varying 145–147
 - of wood 150–152
 - drying air recirculation, solar dryers 232
 - drying costs. *see also* economic aspects
 - drying of timber 235–237
 - drying of tobacco 237–239
 - kiln-drying 255
 - drying curves, for solar drying 226–227
 - drying systems
 - types of 168–169
 - using zeolites 168–173
 - drying technology, heat pump assisted 121–157
 - drying time, kiln-drying 254, 259–262

- e**
- economic aspects
 - solar drying 234–239
 - zeolite-assisted drying 193–194
 - electric fields, applied in separation processes 80–83
 - electrically heated dryers 12–13
 - electroflotation, definition 80
 - electroosmosis, definition 80
 - electrophoresis, definition 80
 - energy analysis
 - dryers 1–43
 - industrial drying 2–3
 - introduction 1–2
 - energy consumption, drying of renewable material 254–270
 - energy costs. *see also* economic aspects
 - carbon dioxide emissions and carbon footprint 15–16
 - and environmental impact 14–16
 - primary energy use 14
 - energy demands, dryers 13–14
 - energy efficiency
 - definition of 173–174
 - and heat recovery 173–180
 - of sludge drying processes 315–318
 - of thermal valorization 321–324
 - energy flow, flat plate solar air heater 204
 - energy inefficiencies
 - evaluation of 5–14
 - other energy demands 13–14
 - thermal 6–8
 - in the utility (heat supply) system 8–13
 - energy issues
 - drying and heat treatment of biomass 245–287
 - osmotic dehydration 99–114
 - energy losses, evaluation of 5–14
 - energy production
 - biomass drying as precondition 271–281
 - biomass heat treatment as precondition 281–287
 - global 246–247
 - energy recovery
 - in a multi-stage system 176–178
 - for a single-stage system 174–176
 - with superheated steam 178–180
 - energy reduction
 - alternative utility supply systems 32–36
 - analysis of dryer energy consumption 38–42
 - basic principles 17–19
 - case study 37–43
 - classification of 26–36
 - direct reduction of dryer heat duty 29–30
 - drying in the context of the overall process 25–26
 - energy targets 16–17
 - heat recovery and heat exchange 31–32
 - pinch analysis 17–25
 - process description and dryer options 37–38
 - reducing heater duty of convective dryer 28
 - setting targets for 16–26
 - in sludge drying 316
 - utility systems and CHP 42–43
 - energy savings
 - by alternative technologies 270
 - in conventional kilns 269–270
 - drying of renewable material 254–270
 - rules for 269–270
 - energy supply system efficiency, improving of 33–34
 - energy targets, for energy reduction 16–17
 - energy usage
 - dryer energy supply 4–5
 - energy cost and environmental impact 14–16
 - evaluation of energy inefficiencies and losses 5–14
 - evaporation load 3–4
 - fundamentals of 3–16
 - energy valorization, sludge properties for 299–300
 - energy yield, of wood 283
 - engineering materials, from lignocellulosic materials 251
 - environmental aspects
 - absorption refrigeration 139
 - chemical heat pumps 135
 - of energy usage 14–16
 - HPD 130
 - refrigerants 125–126
 - SAHPD 140
 - sludge drying 313–314
 - equilibrium model, for solar drying kinetics 227–231
 - evaporation
 - latent heat of 28–30
 - of moisture 154–156
 - evaporation load, for drying 3–4
 - evaporative heat load 29
 - exhaust air
 - dehumidified air drying 171–172
 - heat recovery from 31
 - exhaust air temperature above dewpoint 7
 - exhaust heat losses 6–7
 - extraterrestrial solar radiation 200

f

fans

- energy consumption 265
- in solar greenhouse dryers 220–222
- FC. *see* fixed carbon content
- fibers
 - dimensions of 253
 - elastic properties of 253
 - from lignocellulosic materials 251
- filter aids 93–94
- filter centrifuges 66–69
- filtration 61–80
 - body feed 80
 - cake 61–72
 - capillary pressure 63–64
 - characterization of processes 49
 - crossflow micro- and ultra-filtration 73–75
 - depth and precoat filtration 75–80
 - overpressure 66–72
 - press 70–72
 - saturation 64
 - sieving and blocking filtration 72–73
 - steam pressure 84–85
 - vacuum 65–66
- fixed bed dryers, for biomass 275–276
- fixed carbon content (FC), definition 249
- flash dryers, for sludge 303, 306
- flat plate collectors, types of 205
- flat plate solar air heaters 204–210
 - energy flow of 204
- flax, anatomical structure of 252
- flocculation
 - in separation processes 92–93
 - in sludge 297–298
- flotation processes, density separation 51–54
- fluidized bed dryers
 - for biomass 275
 - for sludge 304
- foaming suspensions, as filter aids 94
- food and agricultural products, drying
 - by HPD 150–152
- food processing
 - comparison of alternative dryer options 41
 - composite curves 39–40
- forced convection
 - direct solar drying 214–218
 - indirect solar drying 218–223
- frame filter press 70
- freeze drying
 - atmospheric 149–150
 - osmotic 109–111
- freons, refrigerants 125–126
- Freundlich isotherm equation 195
- froth flotation 51–54

fruits

- HPD 148–149
- osmotic dehydration 99–115
- solar drying of 213, 217
- fry-drying, of sludge 311–314
- fuel use, convective steam-heated dryers 10
- function separation, principle 87–88

g

- gas turbine CHP system 35
- gasification
 - of sewage sludge 318–320, 323
 - of sludge 296
- GCC. *see* grand composite curves
- GCV. *see* gross calorific value
- global model, of biomass drying 278–281
- grand composite curves (GCC). *see also* composite curves
 - and Appropriate Placement principle 24–25
 - convective steam-heated dryers 20–21
 - food processing 39–40
 - for gelatin process 23–24
 - liquid-phase processes 18
 - splitted 21–22
- grapes, solar drying of 229–230
- gravity sedimentation 55–57
- greenhouse dryers, solar 219–223, 234
- greenhouse gases emissions 245
- gross calorific value (GCV)
 - of lignocellulosic materials 251
 - of wood 283

h

- hardwood, anatomical structure of 252
- HCFCs. *see* hydro-chlorofluorocarbons
- heat consumption, of sludge dryers 315
- heat duty
 - convective dryer 28
 - direct reduction 29–30
 - for inlet air heat exchanger 4
- heat exchange
 - within the dryer 31–32
 - superheated steam dryers 32
- heat load, evaporative 29
- heat losses, from dryer body 7–8
- heat mass transfer, during fry-drying 312
- heat of evaporation, latent 28–30
- heat of wetting, of solids 7
- heat pipes, in heat pumps 134–135
- heat pump dryer efficiency. *see* specific energy consumption
- heat pump drying (HPD) 121–157
 - absorption refrigeration cycle 139–140

- advantages and limitations of 130–131
 - applications of 150–153
 - atmospheric freeze drying and 149–150
 - classification of dryers 123
 - comparison to other commonly used drying methods 130
 - configurations 131–132
 - cycle of 124, 128
 - of food and agricultural products 150–152
 - fundamentals 122–131
 - future research and development needs 156–157
 - infrared-assisted 143–144
 - introduction 121–122
 - microwave-assisted 143–145
 - miscellaneous systems 140–150
 - modified atmosphere 148
 - multi-mode 147
 - options and advances 132–140
 - of pharmaceutical and biological products 152–153
 - and product quality 122, 130, 149–152
 - refrigerants 125–127
 - sizing of components 153–156
 - solar-assisted 140–143
 - and spray drying 147–148
 - time-varying drying conditions 145–147
 - of wood and timber 150–152
 - heat pumps** 132–140
 - absorption refrigeration cycle 138–140
 - cascade systems 133–135
 - chemical 135–138
 - COP (definition) 125, 129
 - COP (values) 132–133
 - for energy reduction 36
 - fundamentals 122–125
 - multi-stage 132–134
 - use of heat pipe 134–135
 - heat recovery**
 - from dryer exhaust air 31
 - and heat exchange 31–32
 - heat requirements, reducing of**
 - inherent 29–30
 - heat supply systems, energy inefficiencies** 8–13
 - heat transfer**
 - in conventional kilns 264
 - during fry-drying 312–313
 - heat treatment**
 - numerical models of 284–287
 - as precondition for energy production 281–287
 - solid wood and other biomass sources 245–287
 - heat value.** *see* calorific value
 - heating**
 - of boiler feedwater 8–9
 - of solids 7
 - heating systems, back-up** 232–234
 - heating value (HV), of sludge** 299–300
 - hemicellulose, as component of lignocellulosic materials** 248–249
 - HHV.** *see* higher heating value
 - high gradient magnetic separation (HGMS), principle** 82
 - high pressure application, dehydration pretreatment** 102
 - high-temperature dryers, and solar drying** 199
 - higher heating value (HHV), of sludge** 299–300
 - horizontal siphon peeler centrifuges** 68
 - hot streams, in dryers** 17–18, 20
 - HPD.** *see* heat pump drying
 - HV.** *see* heating value
 - hybrid drying, of sludge** 311–312
 - hydro-chlorofluorocarbons (HCFCs), refrigerants** 125–126
 - hydrocyclones** 59
 - hygroscopic behavior, of lignocellulosic materials** 282
 - hyperbar disc filters** 65
- i**
- indirect contact drying**
 - drying performances 308–310
 - rotor design 306–308
 - of sludge 305–310
 - indirect dryers, efficiency improvement** 30
 - indirect solar drying**
 - definition 211
 - with forced convection 218–223
 - with natural convection 213–214
 - industrial drying, energy analysis in** 2–3
 - industrial production, part of drying systems in**
 - energy consumption 163
 - inefficiencies.** *see* energy inefficiencies
 - infrared-assisted HPD** 143–144
 - and product quality 143
 - inlet air heat exchanger, heater duty** 4
 - inlet moisture, reducing** 29
 - insoluble solids, in the drying process** 25–26
 - interception, depth filtration** 76
 - interest coefficient, solar drying** 235
- k**
- kiln-drying** 254–257
 - costs 255

- energy savings in 269–270
- and product quality 255, 269
- time 254, 259–262
- kiln efficiency**
 - case studies 266–269
 - theoretical evaluation of 263–266
- kiln structure, heating of** 265
- kilns**
 - air-tightness 268
 - design of 258–259
 - geometrical and thermal characteristics of 266
 - heat transfer characteristics of 264
 - thermal insulation 268
- kinetics, solar drying** 226–231

- /**
- lamella clarifiers, sedimentation basins** 57
- Langmuir isotherm equation** 195
- latent heat**
 - of evaporation 28–30
 - of vaporization 263
- LHV. *see* lower heating value**
- light-sensitive products, requirements for drying** 213
- lignin, as component of lignocellulosic materials** 247–249
- lignocellulosic materials**
 - anatomical structure of 252
 - calorific value 251
 - chemical and energy properties of 250
 - chemical composition of 249
 - dimensions of fibers from 253
 - elastic properties of fibers from 253
 - as engineering material 251
 - heat treatment of 281–287
 - hygroscopic behavior of 282
 - initial water content and lower heating value 322
 - as source for biofuels 247–248
- liquid-phase processes, temperature-heat load diagram** 18
- liquids, clarification of** 48
- local model, of biomass drying** 276–278
- low cost utilities, for energy reduction** 33
- low-temperature convective dryers, GCC** 22
- lower heating value (LHV)**
 - and moisture content 271
 - of sludge 299–300, 313

- m**
- magnetic fields, applied in separation processes** 80–83
- magnetic fishing, principle** 81
- Maillard reactions** 185
- manure drying, zeolite-assisted** 189–191
- mass flows, osmotic dehydration** 100
- mass transfer, during fry-drying** 312–313
- mass transfer kinetics**
 - osmotic dehydration 101–104
 - osmotic solution 103
 - pretreatments 101–102
 - product 102
 - treatment conditions 103–104
- MC. *see* moisture content**
- mechanical flotation apparatus** 53
- mechanical solid-liquid separation** 47–94
 - enhancement by additional electric or magnetic forces 80–83
 - filtration 61–80
 - important aspects of efficient processes 85–94
 - introduction and overview 47–51
 - mechanical/thermal hybrid processes 83–85
- mechanical/thermal hybrid processes** 83–85
- medicinal plants, solar drying of** 211, 217–219, 227–228
- micro-filtration** 74–75
- micro-organisms, pathogenic** 314–315
- microwave-assisted HPD** 143–145
- microwave-assisted osmotic dehydration** 111–113
- microwave drying, of wood** 270
- microwave-vacuum drying** 113
- modeling**
 - of biomass drying 276–281
 - of biomass heat treatment 284–287
 - of osmotic dehydration 104–105
 - of solar drying kinetics 227–231
- modified atmosphere HPD** 148
- moisture**
 - evaporation of 154–156
 - reducing 29
- moisture content (MC)**
 - influence on LHV 271
 - initial 26
 - spatial evolution of 280
 - and thermochemical conversion 272
- molecular sieve, zeolite** 164
- Mollier diagram** 6. *see also* psychrometric chart
- solar drying 229
- spray dryer 185–186, 188
- multi-mode HPD** 145–147
 - and product quality 146
- multi-stage dryers, air dehumidification** 171–172

multi-stage heat pumps 132–134
 multi-stage systems, energy recovery
 for 176–178
 municipal waste, initial water content and
 lower heating value 322

n

natural convection
 – direct solar drying 212–213
 – indirect solar drying 213–214
 net calorific value (NCV), definition 251
 numerical models. *see also* modeling
 – of biomass drying 276–281

o

oak boards, kiln drying of 266–269
 oil burning back-up heating system 233
 on-site integration, of sludge drying and
 thermal valorization 322–324
 open gradient magnetic separation (OGMS),
 principle 83
 osmo-convective drying 107–109
 osmo-freeze drying 109–111
 osmo-microwave drying 111–113
 – specific energy demand 112–113
 osmotic dehydration 99–114
 – combination with other drying
 methods 107–108, 111–112
 – definition 100–101
 – mass transfer kinetics 101–104
 – modeling of 104–105
 – pretreatments 101–102
 – product effect on 102
 – quality issues 105–106
 – treatment conditions 103–104
 osmotic solution, mass transfer kinetics 103
 osmotic-vacuum drying 113–114
 outlet moisture, increasing 29
 overpressure filters 66–72

p

p-h diagram. *see* pressure-enthalpy diagram
 packed bed filters 77
 packed-bed systems, *versus* adsorption
 wheel 181–182
 paddle dryers
 – evaporation performance 309
 – rotor design 306–308
 pan filters 66
 parallel-flow configuration, conveyor
 dryers 280–281
 parallel separation arrangement 90–91
 particle agglomeration, in separation
 processes 92–93

particle scale model, of biomass drying

276–278

pathogen reduction, sludge drying 314–315

payoff period, solar drying 235

PE. *see* polyethylene

peeler centrifuges, horizontal siphon 68

peppermint

– drying characteristics of 228

– drying curve 230–231, 233–234

pharmaceutical products, drying by

HPD 152–154

photovoltaic (PV) generators, in solar tunnel

dryers 214–216

pinch analysis 17–25

– application to dryers 19–21

– Appropriate Placement principle 21–24

– basic principles 17–19

– and utility systems 24–25

plants, drying of. *see* specific types of plants

PMMA. *see* poly(methyl methacrylate)

pneumatic flotation apparatus 53

polyethylene (PE), as transparent cover

material 209, 215, 218–219

poly(methyl methacrylate) (PMMA), as

transparent cover material 209

polytetrafluoroethylene (PTFE), as transparent

cover material 209

polyvinyl chloride (PVC), as transparent cover

material 209

pores, capillary pressure 63

pre-treatment methods, to improve separation

conditions 91–94

precoat drum filters 79

precoat filtration 78–80

press filtration 70–72

– enhanced by electric fields 81

pressure-enthalpy (p-h) diagram, refrigerant

cycle 124–125

product quality

– and atmospheric freeze drying

149–150

– and HPD 122, 130, 151–152

– and infrared-assisted HPD 143

– kiln-drying 255

– kiln-drying of solid wood 255, 269

– and multi-mode HPD 146

– and solar drying 199–200, 212–213

psychrometric charts. *see also* Mollier diagram

– air cycle 128

– energy inefficiency evaluation 5–6

PTFE. *see* polytetrafluoroethylene

pusher centrifuges 69

PVC. *see* polyvinyl chloride

pyrolysis

- of sewage sludge 318–320
- of sludge 296

r

- radiofrequency drying, of wood 270
- recirculation, of drying air 232
- refrigerants
 - fundamentals 125–127
 - identification number for 126–127
- refrigeration cycle
 - HPD 139–140
 - p-h diagram 124–125
- refrigerators. *see* heat pump drying
- renewable material 245–287. *see also* biomass
 - drying as a preconditioning step 271–281
 - energy consumption and energy savings 254–270
 - heat treatment as a preconditioning step 281–287
 - preconditioning of 271–287
 - wood and biomass as a source of 245–254
- roof-integrated solar air heaters, dryers
 - with 223–225
- rotary dryers
 - for biomass 274–275
 - for sludge 304–306
- rotor design, sludge drying technologies 306–308

s

- sage**
 - drying characteristics of 228
 - solar drying of 230–231
- saturation, of filters 64
- saturation deficit, solar drying 228–229
- screw filter press 71
- SEC. *see* specific energy consumption
- sedimentation 54–61
 - swarm 55
- sedimentation basins 56
- sedimentation centrifuges 57–61
- seed drying, zeolite-assisted 191–193
- seed wool
 - chemical composition of 249
 - dimensions of fibers from 253
- separation apparatuses
 - combination of 87–91
 - mode of operation 85–87
- separation processes
 - density 51–61
 - electric or magnetic forces for enhancement of 80–83
 - improvement of conditions 91–94
 - mechanical solid-liquid 47–94

- mechanical/thermal hybrid 83–85
- particle agglomeration 92–93
- separators, disc stack 60
- serial separation arrangement 90
- settling velocity, sedimentation 55
- sewage sludge
 - desired water content for thermal processes 319–320
 - disposal methods 296
 - drying step before thermal valorization 320–321
 - general description of thermal processes 318–319
 - thermal valorization of 318–321
- SG. *see* solids or solutes gain
- sheet filters 78
- sheet glass, as transparent cover material 209
- SHS. *see* superheated steam
- sieving filtration 72–73
- silica gel, adsorption properties 167–168
- simulation. *see* modeling
- single particle model, of biomass
 - drying 276–278
- single-stage systems, energy
 - recovery for 174–176
- sky radiation, solar 202–204
- sliding discharge centrifuges 69
- sludge
 - chemical composition of 297
 - as complex material 297–299
 - decreasing water content 295–296
 - disposal methods 296
 - heating values 299–300, 313
 - initial water content and lower heating value 322
 - origin, production and valorization issues 295–297
 - properties for energy valorization 299–300
 - rheological properties 298
- sludge drying
 - energy efficiency 315–318
 - environmental aspects 313–314
 - specific heat consumption 315
 - zeolite-assisted 189–191
- sludge drying technologies 300–315
 - case studies 316–318
 - combined drying 311
 - convective drying methods and dryer types 301–305
 - general remarks 300–301
 - hybrid drying 311–312
 - indirect contact drying methods and dryer types 305–310

- on-site integration with thermal valorization 322–324
- pathogen reduction 314–315
- reduction of energy consumption 316
- sludge frying 311–314
- solar drying and dryer types 310–311
- sludge flocs 297–298
- sludge frying
 - as alternative drying method 311–314
 - energy and environmental aspects 313–314
 - environmental aspects 313–314
 - heat and mass transfer 312
- sludge gasification 296, 318–320, 323
- sludge siccit, influence on energy balance 323
- sludge thermal processing 295–324
 - energy efficiency of 321–324
 - introduction 295–300
 - sewage sludge 318–321
- SMER. *see* specific moisture extraction rate
- softwood, anatomical structure of 252
- solar air heaters 204–210
 - ASHRAE standard (ANSI/ASHRAE, 1986) 206
 - efficiency of 205–209
 - roof-integrated 223–225
- solar-assisted heat pump drying (SAHPD) 140–143
- environmental impact 140
- schemes of 141–142
- solar cabinet dryers 213–214
- solar collectors
 - absorber materials 208
 - in conventional drying 204–205
 - transparent cover materials 209
- solar constant 200
- solar dryers
 - airflow management during night 231–232
 - back-up heating systems 232–234
 - classification of 210–212
 - control strategies for 231–234
 - design and function of 210–225
 - with forced convection for direct drying 214–218
 - with forced convection for indirect drying 218–223
 - modes of operation 211
 - with natural convection for direct solar drying 212–213
 - with natural convection for indirect drying 213–214
 - recirculation of drying air 232
 - with roof-integrated solar air heaters 223–225
- tent-type 213
- solar drying 199–239
 - annuity 235
 - direct 211–213
 - economic feasibility of 234–239
 - empirical drying curves 226–227
 - equilibrium model for 227–231
 - indirect (*see* indirect solar drying)
 - interest coefficient 235
 - introduction 199–200
 - kinetics of 226–231
 - payoff period 235
 - and product quality 199–200, 212–213
 - saturation deficit 228–229
 - of sludge 310–311
 - solar air heaters 204–210
 - solar radiation 200–204
 - of wood 270
- solar greenhouse dryers 219–223
- with back-up heating system 234
- solar heated air drying 211
- solar radiation, distribution over location and time 200–204
- solar tunnel dryers 214–218
- walk-in 217
- solid-liquid separation processes
 - combination of separation apparatuses 87–91
 - important aspects of 85–94
 - mechanical 47–94
 - mode of operation 85–87
 - suspension pre-treatment methods 91–94
- solid wood 245–287. *see also* wood
- conventional drying 258–262
- energy consumption and energy savings 254–270
- kiln-drying 254–257
- kiln efficiency (case studies) 266–269
- numerical approach to drying 276–281
- rules for saving energy 269–270
- theoretical evaluation of kiln efficiency 263–266
- solids
 - dehumidification 48
 - heat of wetting 7
 - heating 7
 - washing of 49
- solids or solutes gain (SG)
 - effect of mixing on 104
 - mass transfer kinetics 101
- soluble solids, in the drying process 25–26
- solutes, mass flow in osmotic dehydration 100
- sorption, differential heat of 263

- sorption isotherm data, zeolites 195–196
 specific energy. *see* heating value
 specific energy consumption (SEC), heat pumps 129
 specific energy demand, osmo-microwave drying 112–113
 specific heat consumption (SHC), of sludge dryers 315
 specific moisture extraction rate (SMER), heat pumps 129
 spray dryers 38
 – with adsorption system and SHS-cycle 187
 – food processing 41
 – heat pump assisted 147–148
 – Mollier diagram 185–186
 spruce boards, kiln drying of 266–269
 steam consumption, breakdown of 42
 steam distribution losses 9–10
 steam-heated dryers 8–11
 – breakdown of fuel use 10
 steam pressure filtration 84–85
 stirred pressure nutsch filters 66
 Stokes law, settling velocity 55
 straw
 – anatomical structure of 252
 – chemical and energy properties of 250
 – chemical composition of 249
 – dimensions of fibers from 253
 sugar cane bagasse, anatomical structure of 252
 sun drying. *see* solar drying
 superheated steam (SHS) dryers
 – GCC of convective 22
 – heat exchange in 32
 – zeolite-assisted 178–180, 186–189
 surfactants, density separation 52
 suspension pre-treatment methods, to improve separation conditions 91–94
 suspensions, concentration of 48
 swarm sedimentation 55
 synthetic fibers, elastic properties of 253
- t**
 tent-type solar dryers 213
 thermal insulation, and energy consumption 268
 thermal losses, and energy consumption 263–264
 thermal oil systems, convective dryers 10–11
 thermal valorization
 – desired water content for 319–320
 – drying step before 320–321
 – energy assessment of 321–322
 – energy efficiency of 321–324
 – general description of process 318–319
 – importance of dryer efficiency 321–322
 – integrating sludge drying on site 322–324
 – of sewage sludge 318–321
 thermochemical conversion, of biomass 272
 thin film dryers
 – evaporation performance 309
 – rotor design 307–308
 timber
 – HPD of 150–152
 – solar drying of 222–223, 235–237
 timber load, heating of 265
 time-varying drying, and HPD 145–147
 tobacco drying (solar) 220–222
 – in Brazil 237–239
 transparent cover materials, solar collectors 209
 tube centrifuges 58
 tunnel dryers, solar 214–218
- u**
 ultra-filtration 74–75
 unit cell, zeolites 164–165
 utility systems
 – alternative 32–36
 – and CHP 42–43
 – combined heat and power 34–36
 – energy inefficiencies 8–13
 – heat pumps 36
 – improving energy supply system efficiency 33–34
 – low cost utilities 33
 – pinch analysis 24–25
- v**
 vacuum band dryers 37
 – food processing 41
 vacuum belt filters 65
 vacuum drying, of wood 270
 vacuum filtration 65–66
 vacuum tray dryers 37
 – food processing 41
 valorization processes
 – dry solids contents required for 320
 – energy efficiency of 321–324
 – sludge 295–297
 van Meel model, of biomass drying 276–277
 vaporization, latent heat of 263
 vegetables
 – HPD 146–149
 – osmotic dehydration 99–115
 vibrating screen centrifuges 69
 volatile matter (VM), definition 249

w

- walk-in solar tunnel dryer 217
- wastewater treatment plants (WWTP) 295. *see also* sludge
 - energy assessment 316–318
 - water, mass flow in osmotic dehydration 100
 - water adsorption. *see* adsorption
 - water loss (WL)
 - effect of mixing on 104
 - mass transfer kinetics 101
 - water systems, convective dryers 10–11
 - weight reduction (WR), mass transfer kinetics 101
 - wheat straw, anatomical structure of 252
 - WL. *see* water loss
 - wood. *see also* biomass; renewable material; solid wood
 - anatomical structure of 252
 - chemical and energy properties of 250
 - chemical composition of 249
 - dehumidification 270
 - dimensions of fibers from 253
 - drying by HPD 150–152
 - energy yield 283
 - GCV 283
 - mechanical properties after heating 284
 - microwave drying 270
 - most important drying phenomena 256
 - radiofrequency drying 270
 - solar drying 270
 - as a source of renewable material and energy 245–254
 - spatial evolution of average moisture content 280
 - vacuum drying 270
 - wood chips, in conveyor dryer 279

worm screen centrifuges 69

WWTP. *see* wastewater treatment plants

z

- zeolite-assisted drying
 - air dehumidification 168–173
 - in the dairy industry 185–189
 - direct-contact 168–170, 191–193
 - economic considerations of energy reduction 193–194
 - energy efficiency and heat recovery 173–180
 - introduction 163–164
 - manure and sludge drying 189–191
 - multi-stage systems 176–178
 - perspectives in energy reduction 195
 - realization of dryer systems 180–185
 - single-stage systems 174–176
 - superheated steam systems 178–180
- zeolites 163–196
 - adsorption heat 165
 - as adsorption material 164–168
 - adsorption wheel 183–185
 - adsorption wheel *versus* packed bed 181–182
 - compared with other adsorbents 166–168
 - crushing strength 183
 - drying projects with 185–193
 - in drying systems 168–173, 180–185
 - long term capacity of 183
 - mechanical strength 182–183
 - regeneration of 164, 167–169, 172, 190, 192
 - sorption isotherm data 195–196
 - unit cell 164–165