Index

a

acetogenic step 76, 474
acetoin 82–84, 422–425, 427–429, 505–509
acid-base equilibria 36, 77
acidogenic step 76
adaptive control 154, 410–412, 415–416
aerated bioreactor 39, 121, 410
aerated tank, biological oxidation in 115–117
aeration efficiency 109
aeration of a tank reactor for enzymatic oxidation (OXENZ) 70, 329–332
aerobic ethanol fermentation 260
air distribution efficiency 47
algebraic loop iteration 37
allosteric kinetics 64
anaerobic degradation kinetics 76–77
anaerobic reactor activity measurement (ANAEMEAS) 77, 473–479
animal cells 34, 68–70, 145, 374, 441, 509–517
Arrhenius equation 65, 67, 238
artificial neural networks 155
automatic feedback process control
  advanced control strategies 153–155
  application strategies 155–157
  controller action, types of 147–150
  controller performance 152–153
  controller settings 152
  controller tuning 150–151
    trial and error method 151
  elements of 144
  process variables, measurement of 144–147
  purpose of 143
  ultimate gain method 152
  Ziegler–Nichols method 151–152
automatic reset 148

b

Bacillus subtilis
  culture 81–84
  fermentation 84
  strain 422
baker's yeast 78, 156, 487
  oscillation models 80–81
balance region 15–17
  interphase mass transport 21
  transport system identification 17
  tubular reactor 16
  around well-mixed continuous reactor 15
batch bioreactors
  characteristics 49
  cell model 164
  periods of operation 49
  with continuous aeration 116
batch fermentation (BATFERM) 23, 42, 65, 69, 70, 72, 92, 93, 98, 111, 199–204, 205, 209, 397, 495–496
batch heat sterilization (BATSTER) 42, 67, 237–242
batch nitrification with oxygen transfer (NITRIF) 70, 120, 337–340
batch reactors 473
  BATSTER 237–242
  corona virus, growth of 242–246
  kinetics of enzyme action (MMKINET) 229–231

Biological Reaction Engineering: Dynamic Modeling Fundamentals With 80 Interactive Simulation Examples, Third Edition. Elmar Heinzle, Irving J. Dunn, John Ingham, and Jiří E. Přenosil.
© 2021 WILEY-VCH GmbH. Published 2021 by WILEY-VCH GmbH.

Lineweaver–Burk Plot (LINEWEAV) 231–234
OLIGO 234–237
batch stirred tank model 42, 237
biocatalyst diffusion model, coupling to continuous tank model 134
biofilm 135
column reactor 385
nitrification reactions 138–141
oxygen diffusion effects 138
biofilm reactor 117–120, 321, 326, 468, 470
biofiltration column for removing two inhibitory substrates (BIOFILTDYN) 102, 349–354
biofloc 127, 131, 135, 138, 374
biological oxidation, in aerated tank 115–117
biological oxygen uptake rate 111
biomass 159
formation 65
productivity 97–98
recycle 98–100
retention 100
wastage rate of 99
biomass yield coefficient 100, 223
on substrate 33
bioprocess variable measurement 145
calculated variables 146
dynamic characteristics 146–147
using sensors 145–146
bioreactor(s)
batch operation 48–50
continuous operation 51–54
hydrodynamic environment, physical factors affecting 47
modes of operation 55
operating variables 55
semi-continuous/fed batch operation 50–51
bioreactor modeling
information for 47–48
tank-type 91–102
tubular reactor 103–104
bioreactor performance
empirical procedure 4
modeling approach 4–6
advantage 4
formulation 3
Briggs–Haldane mechanism 59
butanediol 82–84, 422–424, 426, 428–429, 505–509

C

carbon dioxide evolution rate (CER) 448, 449
carbon dioxide production rate (CPR) 5, 80, 145–146
cascade control 153, 154
cell growth rate 5, 22, 47, 57, 290
cell kinetic models 57, 58, 78
cell model 160
and continuous well-mixed stirred tank bioreactor 162–164
batch bioreactor 164
biomass 161
compartmented cell 165
metabolite balance equation 160, 161
schematic illustration 160
variables 160
cell retention membrane reactor (MEMINH) 71, 100, 111, 419–422
chemical equilibrium 35, 474
chemical production rates 22
chemical reaction 91, 111, 355, 480
chemostat 93–96, 100, 145, 275–278, 279, 290, 294–297, 298, 408, 452, 461–462, 465–466
cell model 162–164
chemostat fermentation (CHEMO) 52, 69, 72, 93, 204–208
CHO cell cultivation 90
circulation time 47
closed-loop feedback control 143–144, 151–152
column reactor 51, 53, 122, 301, 385–386, 441
commensalism 73–75, 452–456
competition between organisms (TWOONE) 75, 465–467
competition between two microorganisms for an inhibitory substrate in a biofilm (FILMPOP) 468–473
complex river flow system 16–17
component balances 14, 18, 24–29, 93, 103, 134, 140, 163, 167–168, 215, 255–256, 261, 306, 318, 345, 386–387, 437

equation 21
with reaction 14
component mass balance, for reacting systems 24
constant volume continuous stirred tank reactor 25–26
semi-continuous reactor with volume change 26–27
computational fluid dynamics (CFD) modeling 121–122
computational tools 8
computer simulation methods 8
contact thermometer 147
continuous baker's yeast culture, oscillations of 80–81
continuous culture with inhibitory substrate (CONINHIB) 52, 70, 95–96, 277–283
continuous enzymatic reactor (ENZCON) 26, 64, 310–312
continuous production of PHB in a two-tank reactor process (PHBTWO) 54, 64, 70, 72, 78, 79, 101, 317–320, 494
continuous reactors 423
ACTNITR 283–287
CHEMOSTA 275–278
concentration profiles 52, 53
CONINHIB 278–283
DCMDEG 321–328
DEACTENZ 313–317
DUAL 290–294
ENZCON 310–312
ENZTUBE 287–290
FBR 301–305
NITBED 305–310
operation characteristics 53
PHBTWO 317–320
STAGED 298–301
startup of 52
TWOSTAGE 294–297
types 51, 52
continuous stirred tank bioreactor 15–16
continuous-cycling method 152
control of a continuous bioreactor with inhibitory substrate (CONTCON) 405–410
controlled reactors
CONTCON 405–410
FERMTEMP 397–402
TEMPCONT 393–397
TURBCON 402–405
controller action, types of 147–150
controller tuning
purpose of 150–151
ultimate gain method 152
Ziegler–Nichols method 151–152
convective flow 19, 23, 110, 195
for well-mixed tank bioreactor 19
convective transfer flows 17
corona virus (CORONADYN) 14, 67, 242–246

d

D-value 67
Damköhler Number 137
diauxic Monod growth 71
dichloromethane in a biofilm fluidized sand bed (DCMDEG) 36, 38, 120, 123, 321–328
differential equations 7, 9–11, 37, 66, 103–104, 112, 123, 134, 136–137, 139, 141, 143, 149, 153, 159, 243, 361, 480–481
time constants derivation from 43–45
diffusion
of components 20
film 128
diffusion systems
BIOFILM 361–365
CELLDIFFCYL 378–384
ENZDYN 369–374
ENZSPLIT 366–369
NITBEDFILM 385–391
diffusion-reaction equations 361, 469
diffusive transfer flows 17
digital simulation languages 7, 13
dimensionless model 481–482
dimensionless model equations 345, 348, 368
discontinuous control 147
dissociation equilibrium constant 36
dissolved oxygen tension (DOT) 448, 449
Double Michaelis–Menten Kinetics 62
Double Monod kinetics 71
double substrate biofilm reaction (BIOFILM) 44, 71, 134–135, 138, 140–141, 361–365, 469

dry mass (DM) 79, 159, 199, 492
dual substrate limitation (DUAL) 54, 70, 101, 290–294
dynamic bioprocess modeling
  eukaryotic cells, protein synthesis and secretion 193–194
  lake 191–192
  liver sinusoid model 194–196
  mammalian cell recirculation reactor 192–193
  Roman fountain 190–191
dynamic porous diffusion and reaction (ENZDYN) 369–374
dynamic simulation 8, 11, 37, 104, 144, 190, 204, 249
dynamic total mass balance 13

e

effective diffusivity 20
effectiveness factor 137–138, 371, 375, 376, 381
ELECTFIT program 44, 112, 147, 343–349
elemental balances 14, 31–32, 253
elemental balancing technique 29–33, 252–260
energy balances 4, 13
energy balances, for bioreactors 38–39
  accumulation term 39
  heat transfer term 41
  liquid flow term 39–40
  reaction heat term 41–42
  rules 38
  water evaporation term 40–41
energy yield coefficients 34–35
enthalpy 35, 39, 238–240, 253–254
enzymatic lactose hydrolysis 234–237
enzymatic tanks-in-series bioreactor system 100–102
enzyme deactivation 65, 67, 314
enzyme kinetic models 58
  allosteric kinetics 64
  double Michaelis–Menten kinetics 62
  inhibition 62–63
  reaction equilibrium 58
  substrate inhibition 63–64
  temperature and pH influence 64–65
enzyme-substrate complex 43, 59, 229, 234
equilibrium 4, 23, 35–37, 58, 77, 107–110, 116, 148, 218, 323, 333–334, 344, 352, 424–426, 474–476, 497
error integrals, controller performance characterization 152–153
ethanol fed batch diauxic fermentation (ETHFERM) 51, 144, 260–264
eukaryotic cells, protein synthesis and secretion 193
evaporation 39–41, 255
exergonic reaction 35
exocytotic process 193
Eyring equation 238

f

fast equilibrium reactions 44
fed batch bioreactors 50
  cell balance 51
  characteristics 50
  configuration 50
  feeding strategies 50
  substrate concentration 51
fed batch fermentation (FEDBAT) 27, 51, 69, 72, 97, 208–212, 247, 259, 264, 270
fed batch fermenter 96–98, 157, 208, 270–273
fed batch fermenter mode 247
fed batch reactors
  cell balancing 225–227
  cell growth 218–219
  ETHFERM 260–264
  PENOXY 270–273
  REPFED 264–267
  REPLCUL 267–269
  VARVOL and VARVOLD 247–252
fed-batch bioreactor 50, 154, 511
feedback control of a water heater (TEMPCONT) 42, 144, 147, 149, 151–153, 393–397
feedforward control method 153–154
fermentation
  steady-state oxygen balance 27–28
  with biomass recycle 98–100
fermentation with pervaporation (PERVAPSUB)
  acetoin formation 424
  butanediol formation 424

dynamic reactor mass balances 425–426
growth 423–424
nomenclature 426–427
pervaporation model 425
reaction rates 424–425
results 429
system 422–423
Fick's law 107, 128, 131, 362, 387
for molecular diffusion 20
finite differencing techniques 20, 370
first order reaction rates 55, 61, 65, 130, 132, 137–138, 215, 255, 313
flow velocity 23, 102, 130, 288–289
fluidized bed biofilm reactor, nitrification in 117–120
fluidized bed recycle reactor (FBR) 115, 120, 123, 301–304
fuzzy control 155

g

β-galactosidase 313
gas and liquid oxygen dynamics in a continuous fermenter (INHIB) 70, 71, 111, 148, 331–335
gas holdup volume 23, 47, 121
gas-liquid interface
concentration gradients at 107
mass transfer in 105–106
generalized oxygen balance equations for gas-liquid transfer 109–120
glucose oxidase (GOD) 112
Golgi complex (GC) 193

h

Haldane kinetics 468, 470
heat effects 39, 42, 397
heat production rate determination 42
heat sterilization 38, 67, 237–242
heat transfer 41, 144, 400
heat transfer area, of reactor 42–43
heat transfer coefficient 41, 238
Henry's law 23, 108–109, 121, 218, 344
volatility constant 108
HepaRG cells 170–171
hepatocytes 115, 189, 192, 194–196, 374
Hill kinetics 64
host-virus interaction, in population 74

i

Ideal Gas Law 18, 23, 28, 108, 116, 224, 344, 412
immobilized animal cells in a fluidized bed reactor (ANIMALIMMOB) 71, 120, 441–446
immobilized biocatalyst systems 127
concentration profiles 128
dimensionless parameters 136–137
effectiveness factor 137–138
external mass transfer 128–130
finite difference method
for diffusion-reaction flat plate systems 132–135
finite difference model
for diffusion-reaction in sphere 135–136
overall reaction rate characteristics 131
immobilized biofilm in a nitrification column system (NITBEDFILM) 140, 306, 385–391
immobilized enzyme 105, 141, 287, 313, 361, 435
inert gas balance 28–29
information flow diagram 23
of batch fermenter model equations 200–201
for modeling approach 7
Inhibition kinetics 62–64, 85, 89, 473–476
allosteric 64
irreversible 65
of enzyme 62–64
of growth 69
product inhibition 54–57, 64, 70, 73, 75, 101, 298–300, 310–315, 317–318, 430, 442, 447–450
substrate inhibition 54–56, 63–64, 77, 95–96, 215–216, 218, 235, 260, 278–283, 289, 296, 321, 332–335, 349–352, 362–372, 405–407, 419–421, 423, 468–472, 492–494, 511–514
Inhibitor 62–63, 69, 85, 447–450, 497–498
integral viable cell density (IVCD) 511–513, 515–517
integration procedure 12–13

intensity of mixing 47, 123
interacting (micro-)organisms 72–77
interfacial transfer flows 17
internal concentration profiles, in symmetrical rectangular biocatalyst matrix 131
internal mass transfer 127
interphase gas-liquid mass transfer 106–109
interphase mass transport 21
interphase transfer flows 17
intraparticle transfer 128
ion charge balance, for pH calculation 36–38
isotope tracers 95

k

kinetics of enzyme action (MMKINET) 61, 229–231
KLADYN program 44, 113, 137, 147, 343–349
KLAFIT program 44, 147, 343–349
Klebsiella oxytoca 447

l

lake model 191–192
lin-log approach 85
Lineweaver–Burk Plot (LINEWEAV) 61, 231–234
liquid flow pattern 47
liquid–liquid extraction 105, 106
liver sinusoid model 194–196
log-lin approach 85
logistic equation 70–71
Luedeking–Piret model 72, 89, 402
Luedeking–Piret-type expression 317

m

macroscopic kinetics 57
Madonna programs 201, 257, 264, 276, 412, 519
MADONNA simulation software 213
maintenance coefficient 5, 207, 420
maintenance factor 71
mammalian cell cultivation, in fed-batch cultures 31, 49, 88–90, 156–157
mammalian cell recirculation reactor modeling 189, 192–193
mass balance 4, 362, 480
mass balance equation
  derivation of 11–12
    computer solution 12–13
    numerical integration procedure 13
    using rates 11–12
  river with eddy currents 16–17
  types of 13–14
mass transfer capacity coefficient
  chemical/biochemical reaction 111–112
  dynamic method 112–113
mass transfer, in biological systems 105
  gas–liquid interface 105, 106
  interphase gas–liquid mass transfer 106–109
  liquid–liquid interface 105, 106
  porous biocatalyst, diffusion and reaction in 106
  surface biocatalysis 105, 106
mass yield coefficients 33–34
mathematical models 4, 6–7, 132, 290, 344
MATLAB-SIMULINK 8
membrane and cell retention reactors
  ANIMALIMMOB 441–446
  LACMEMRECYC 430–435
  MEMINH 419–422
  PERVAPSUB 422–430
metabolic network model 84, 487–520
metabolic network stoichiometry 30–31
metabolic steady state, in batch culture 164–165
methanogenic step 76–77
methyl ethyl ketone (MEK) 350–353
methyl isobutyl ketone (MIBK) 350–352
Michaelis–Menten constant 60, 130, 233
Michaelis–Menten equation 57, 58–61, 62, 65, 229, 367
Michaelis–Menten kinetics 61, 62, 68, 129–130, 231, 232, 313
Michaelis–Menten product inhibition model 235
Michaelis–Menten simplification 230, 231
microbial interaction 73
  commensalism 73–74
  mutualism 74
  predator-prey kinetics 73

microbial kinetics 65
cell death and sterilization 67
cell growth kinetics 66
Monod growth kinetics 68–69
product formation 72
product inhibition 70
specific growth rate, expressions for 70–71
specific rates 67–68
substrate inhibition 69–70
substrate uptake kinetics 71
wastewater treatment systems, substrate uptake in 72
mixing 19, 42–45, 47, 52–53, 81, 102, 120–121, 123–124, 145, 219, 505
modeling approach 4
advantage 4
and simulation approach 5–6
balancing procedure 15–23
features 6
formulation 3
stages 6–7
teaching applications 8–9
molar stoichiometry 26
molecular diffusion 20, 107
Fick's law for 20
molecular mechanism 497
Monod equation 57, 68, 70, 72, 75, 199, 248, 278–279, 298
Monod function for oxygen 419
Monod kinetics 4, 69–71, 94, 207, 217, 267, 276–277, 293, 473
Monod model 456
Monod-type equation 254, 285, 375
multi-organism systems
ANAEMEAS 473–479
COMMENSA 447–451
FILMPOP 468–473
MIXPOP 461–465
TWOONE 465–467
multiphase reaction systems 105
multiple-substrate Monod kinetics 70–71
mutualism 74, 75–76
mycelium 252, 256

n

Nernst-diffusion film 128
NITBEDFILM 140, 306, 385–391
nitrification in a fluidised bed reactor (NITBED) 70, 123, 305–310
nitrification in activated sludge process (ACTNITR) 75, 100, 283–287
nitrification
biofilms 138–141
in fluidized bed biofilm reactor 117–120
nitrifiers 283, 286, 305
non-linear partial differential equations 361

o

oligosaccharide production in enzymatic lactose hydrolysis (OLIGO) 93, 234–237
on-off controller 147
open-loop feedback control 143, 151, 152, 154
optimal feeding profiles 143
organism modeling 168–171
oscillations in continuous yeast culture (YEASTOSC) 487–492
oxygen absorption 106
oxygen balance 21, 27, 109–120, 123, 136, 302, 306, 332, 335, 340, 344, 375, 378, 387, 411, 420, 448
oxygen diffusion to a single cell/cell aggregate (CELLDIFFCYL) 44, 136, 141, 145, 378–384
oxygen electrode dynamic model 344–345
oxygen mass transfer rates 47, 121, 332
oxygen transfer models, in large scale bioreactors 120–122
bubble column bioreactor 122–123
multiple impeller fermenter 123–126
oxygen transfer rate (OTR) 5, 111, 115, 218, 355, 419, 449
oxygen uptake and aeration dynamics (OXDYN) 44, 114, 147, 340–343
oxygen uptake rate (OUR) 5, 27–28, 42–43, 80, 448
oxygen uptake rate determination
by dynamic method 113–114
steady state gas balance equation for 111
steady-state liquid phase balance equation 114–115

oxygen uptake systems
BIOFILTDYN 349–354
INHIB 332–336
NITRIF 336–340
OXDYN 340–343
OXENZ 329–332
oxygen electrode methods 343–349
oxygen-sensitive *Bacillus subtilis* culture 81–84
oxygen diffusion effects, in biofilm 138

p

pandemic model (SIRDYN, SYRDYNDIM) 74, 479–485
penicillin fermentation using elemental balancing (PENFERM)
balance equations 255–256
biomass formation rate 254–255
elemental balancing 252–258
feeding of glucose 252
glucose uptake rate 254
Madonna program 257
metabolic relationships 256–257
precursor consumption rate 254
rate of penicillin hydrolysis 255
rate of penicillin synthesis 254–255
penicillin production in a fed batch fermenter (PENOXY) 51, 70, 270–273
perfusion cultivation 100
pH calculation 36–37
phenylpropanoid pathway 86–88, 501
physical models 6, 9, 14
PI controller 148–149, 217–218, 222, 401, 407, 410–411, 413
plug flow idealization, of tubular reactor 102
poly-β-hydroxybutyric acid (PHB) growth and synthesis 79
porous biocatalyst 106, 369
predator-prey kinetics 73
predator-prey population dynamics (MIXPOP) 75, 461–465
process optimization 5–6, 48, 155
process reaction curve 151
product formation kinetics 72, 200
product inhibition 56, 57, 63–64, 70, 73, 75, 101, 235, 298–301, 310–311, 313–315, 318, 367, 423, 430
product inhibition kinetics 54, 70, 314
programmed adaptive control 154
proportional (P) controller 148
proportional-integral (PI) controller 148–149, 217
proportional-integral feedback controller 394
proportional-integral-derivative (PID) controller 149–150
proportional-reset-rate-control 149
protein synthesis and secretion, in eukaryotic cells 189, 193–194
Pseudomonas aeruginosa 447

r

rate of accumulation of mass 11, 13–14, 18, 22, 24, 51
reaction enthalpy 35
reaction heat 38, 41
reactor cascade with deactivating enzyme (DEACTENZ) 313–317
reactor-membrane system 419
receptor binding 35–36
recirculation reactor 189, 192–193, 441
repeated fed batch culture (REPFED) 27, 51, 97–98, 264–267
repeated medium replacement culture (REPLCUL) 27, 51, 97, 267–269
reproduction number 481, 482
respiration quotient (RQ) 5, 256
reversible enzymatic inhibition kinetics 62
Roman fountain modeling 190–191

s

saturation constant 4, 68, 69, 453, 470, 511
scheduled adaptive control 154
secondary metabolite synthesis pathway 85–88
selectivity 34, 156, 428–429
semi-continuous bioreactors 50–51
sensor 43–44, 144–147, 156, 217, 234, 355–356, 379, 394, 411
shear effects 48
shear thinning 48
simple structured models 78
continuous baker's yeast culture, oscillations of 80–81

oxygen-sensitive *Bacillus subtilis* culture 81–84
PHB growth and synthesis 79
simulation approach 5
and modeling approach 4–6
simulation tools 8
SIR model 74, 479–486
solid biocatalyst 105, 106, 361
specific carbon dioxide production rate 5
specific growth rate 4, 66–71, 77, 89, 94–95, 100, 201, 204, 223, 255–256, 278, 283, 291, 317, 408–408, 413, 415, 424, 447–448, 453, 457, 465, 469, 470, 474, 495, 510–512
specific heat production rate 5
specific oxygen uptake rate 5, 43, 375, 379
specific product formation rate 5
S-systems approach 85
steady state balancing, for tubular reactors 102–103
steady state gas balance equation, for oxygen uptake rate determination 111
steady state tubular reactor design equation 103
steady-state chemostat (CHEMOSTA) 93–95, 97–98, 207, 275–278
steady-state deoxygenated feed method 115
steady-state dissolved oxygen difference measurement 115
steady-state oxygen balance 27, 448
steady-state split boundary solution (ENZSPLIT) 64, 134, 141, 366–369
steady-state total mass balance 13
stoichiometric coefficients 29–31, 35, 424–425
stoichiometry 26, 29–33, 72, 78, 83, 91, 111, 120, 164, 217–218, 307, 313, 337, 364, 367, 388, 475, 506
black box 32
metabolic network 30–31
simple 29–30
stoichiometry relations 29
Streptrococcus faecalis 430
structured kinetic models 5, 57, 77–90, 317
suberin-lignin-like polymeric material 85–88, 501
substrate inhibition kinetics 63–64, 69, 95, 97, 216, 315, 419
substrate inhibition systems 54
sugar concentration 236, 237
sulfite method 112
surface biocatalysis 105–106

t

tank reactors 53–54
tank-type biological reactors
batch fermenter 92–93
biomass production rates 98
cell and substrate concentration 91
chemostats 93–96
fed batch fermenter 96–97
kinetic rate expression 91
material balance equations 91
organism balance 92
rate expressions 91
substrate balance 92
total mass balance 91
volumetric flow rate 91
yield coefficient 92
tanks-in-series bioreactor system 100–102
tanks-in-series model 135, 195, 289, 441
tanks-in-series reactors 56, 101, 313, 386
Taylor's method 453
temperature control of fermentation (FERMTEMP) 42, 144, 147, 149, 151, 153, 155, 397–402
thermodynamics
and equilibrium relationships 35–38
Thiele Modulus 137, 138
time constants 43–45, 113, 137, 344, 456, 457
from capacity and rate 45
from differential equations 44–45
total mass balance 13, 23–26, 91, 93, 213, 219, 220, 255, 261, 511
of arbitrary system 23–24
toxicity
prediction, bioreactor and human-body model for 169–171
trial and error method 151, 368
trisaccharides 234

tubular enzyme reactor (ENZTUBE) 103, 287–290
tubular plug flow bioreactors
  steady state balancing 102–103
  unsteady-state balancing 103–104
tubular reactors 16, 52–54, 56, 101, 102–104, 115, 288, 435
  concentration characteristics 53–54
turbidostat 95, 402–405
turbidostat response (TURBCON) 44, 72, 95, 144, 147, 149, 153, 402–405
two bacteria with opposite substrate preferences (COMMENSA) 71, 73–74, 93, 447–451
two stage culture with product inhibition (STAGED) 38, 54, 70, 102, 298–301
Two-Film Theory 106, 107
two-stage chemostat with additional stream (TWOSTAGE) 54, 101, 294–297
two-stage fermentor with cell recycle for continuous production Of lactic acid (LACMEMRECYC) 64, 102, 430–435

u

ultimate gain method 152
uncompetitive product inhibition 63
unsteady-state balancing, for tubular bioreactors 103–104
unstructured kinetic model 57

v

valproic acid
  in vitro chronic exposure 170–171
  reverse dosimetry 170–171
variable volume fermentation (VARVOL and VARVOLD) 27, 51, 97, 137, 247–252
viable cell density (VCD) 510–518

w

wastage rate, of biomass 99
wastewater 52, 72, 99, 117, 153, 305, 385, 468, 473, 479
wastewater treatment systems, substrate uptake in 72
well-mixed stirred tank bioreactors
  enzyme reaction 215
  filling and emptying 213, 219
  growth kinetics 217
  operating 220
  operation control 216–217, 221–223
  oxygen transfer and control 217–218, 223–224

y

yeast culture oscillations 80–81, 487
yield coefficients 22, 33–34
  energy 34–35
  mass 33–34

z

zero order reaction rates 55, 129, 132, 137, 138
Ziegler–Nichols method 151–152