## Index

Absorption, 187	packed column absorbers, 189–192,
absorption factor, A, 211, 212	200-227
Chen equation (column diameter), 208	typical packings, 193, 194
Chen equation (number of theoretical	"rules of thumb" for design of packed
trays), 229	columns, 224
Coburn's equation, 211	tray column absorbers, 196, 227-235
column diameter, 207-210	bubble-cap tray absorbers, 197, 198
column height, 210-212	sieve tray absorbers, 199, 200
flooding (flooding velocity), 207	Activity coefficient, 61
height of a single transfer unit,	NRTL equation, 62
H <sub>OG</sub> , 210, 212	parameters, 64
key equations for absorption calculation,	Wilson equation, 62
242, 243	parameters, 63
Kremser-Brown-Sounders equation	Adsorption, 245
(number of theoretical trays), 229	breakthrough point, 266
loading, 207	activated alumina, properties of, 248
minimum liquid-to-gas ratio, 202	activated carbon pressure drop curves
number of overall transfer units, N <sub>OG</sub> ,	(EPA chart), 270
210-212	activated carbon, properties of, 248
Nog for column with constant	adsorbate/adsorbent, 245
absorption factor, 211	adsorbent activation, 246
overall efficiency of bubble-cap tray	adsorbent capacity, 246
absorbers, 230, 231	adsorption equilibria, 250
packing height as function of	adsorption isotherms of carbon dioxide
efficiency & packing size	on activated carbon, 255
(ceramic), 223	breakthrough capacity (BC), 266
packing height as function of	breakthrough curve, 265
efficiency & packing size	chemisorption, 246
(plastic), 222	critical diameter, 246
pressure drop through packed	equilibrium capacity (CAP), 266
column, 224	Freundlich equation, 253
theoretical stage, 228	heat capacities of common adsorbents
weeping, 228	(ambient conditions), 269
Absorption equipment, 189	heat of adsorption (chemisorption vs.
absorption column, 191	physisorption), 252
packed vs. trayed column	HEEL, 266
comparison, 241, 242	Langmuir isotherms, 253, 254

Mass Transfer Operations for the Practicing Engineer. By Louis Theodore and Francesco Ricci Copyright  $\bigcirc$  2010 John Wiley & Sons, Inc.

Adsorption (Continued)	Bubble point calculations
mass transfer zone (MTZ), 265	bubble point pressure (BPP), 50, 166, 175
molecular sieve pressure drop chart, 270	bubble point temperature (BPT), 167
molecular sieves, properties of, 249	Buffer region, 81
physisorption, 245, 246	
regeneration of adsorbent, 251, 266	Cascade, 116
saturation capacity (SAT), 266	Celsius scale, 20, 21
silica gel, properties of, 249	Centrifugation, 471
"sorption" 245	Chemical engineering, 3
vapor/solid equilibrium	history of, 4
(Adsorption) isotherms	Chemical reactions, 39, 40
carbon dioxide on molecular	Conservation law, 8
sieves, 252	Continuous-contact operation, 116, 117
carbon tetrachloride on activated	Controlling resistance, 89-90
carbon, 65	controlling films for various systems, 90
selected hydrocarbons on activated	Convection
carbon, 251	convective transfer, 8
working capacity/charge (WC),	Conversion factors, See "Units"
266, 267	Cooling towers, 340-343
Adsorption equipment, 257	Critical properties
adsorption cycle vs. desorption	critical temperature, 42
cycle, 259	Crystallization, 371
classification of adsorption/desorption	agglomeration, 381, 389
cycles, 283	crystal growth, 379, 380
contact condensers, 263	crystal size distribution (CSD), 381,
continuous rotary bed, 261	386, 387
overall design procedure, 271	crystallization processes, types of, 372
surface condensers, 263	design considerations, 397, 398
Adsorption isotherm, See also "Adsorption"	efficiency of crystallization separation,
adsorbent capacity, 65	390, 391
adsorption equilibrium, 64	magma, 393
BET isotherm, 66	mixed magma underflow, 381
Freundlich isotherm, 65, 66	mother liquor, 371, 381
Langmuir isotherm, 66	nucleation, 372
Polanyi potential theory, 66, 67	occlusion, 393
Antoine equation, 47–49, 166	schematic diagram of generalized
coefficients, 48	crystallization process, 380
Apparent rejection, 423	seeds, 380
Atomic mass units, 23	surface area ration (SAR), 389
•	
Atomic weight, 23	volume ratio (VR), 389
Avogadro's number, 23	Crystallization equipment
Danhauss 461	crystallizers, types of, 392, 393
Baghouse, 461	forced circulation crystallizer, 399
collection efficiency of a baghouse, 462	Swenson-Walker crystallizer, 392
Darcy equation (pressure drop), 463	evaporative crystallizer line diagram, 394
gas-to-cloth (G/C) ratio, 462	Cunningham correction factor (CCF),
Barometer, 22	444, 458
Batch operation, 108	Cyclones, 449
Boiling	critical diameter, 450

cut diameter, 450	constant molal overflow, 142
Lapple calculation procedure, 451	distributed vs. undistributed
multiclone, 449	components, 163
Theodore-De Paola Equation, 453	entrainment (entrainment flooding
	point), 140, 159
Decanter, 264, 475	equilibrium stage, 122
horizontal decanter schematic, 476	ethanol/water equilibrium diagram
settling time, 476	(via Wilson equation, 1atm), 124
Degrees of freedom, 44, 45, 375	Fair flooding correlation, 159, 180, 181
Density	feed condition factor, q, 146, 147
of air, 25	feed tray, graphical location of, 149
of water, 25	Fenske equation (minimum theoretical
Dew point, 41	stages), 168, 177
Differential element, 9	Fenske-Underwood-Gilliland (FUG)
Diffusion	shortcut method, 161-173
Fick's first law, 73, 74	flash distillation, 120-127
molecular diffusion, 43	graphical solution of binary
Diffusion, steady state molecular	flash, 122
in gases, 75	multicomponent flash, 125-127
diffusion in multicomponent	fractional recovery, 164
mixtures, 76	Gilliland correlation (number of
diffusion of A through non-diffusing	theoretical stages), 169-170, 178
B, 75, 84, 85	height equivalent to a theoretical plate
equimolar counterdiffusion, 76, 83, 84	(HETP), 184, 185
equimolar counterdiffusion and/or	internal reflux ratio, 143
diffusion in dilute solutions,	key components, 162
88-90	Kirkbride equation (theoretical feed
in liquids, 79	tray location), 171, 179
diffusion of A through non-diffusing	McCabe-Thiele graphical method,
В, 80	142–158
equimolar counterdiffusion, 80	step-by-step procedure, 152-154
Diffusion, thermal diffusion, 102	overall efficiency, 154, 171-173
Diffusion, turbulent diffusion, 80	O'Connell correlation, 171-173,
Diffusivity, 74, 82	179, 180
estimation methods for gases, 78-79	partial condensation, 121
estimation methods for liquids:	phase equilibrium constant, K, 121
Wilke-Chang equation, 80	pinch point, 152
of common gases at, 0°C, 78	q-line, 148
of water vapor in air at, 25°C and,	Rachford-Rice equation, 125-127
1 atm, 366	Rayleigh equation, 127-133
Distillate, 119	reboiler pressure, 167
Distillation, 119	rectification section, 119, 135
approach to flooding velocity, 159	rectification section operating line
batch distillation, 127–133	(ROL), 144
boil-up ratio, R <sub>B</sub> , 135	reflux ratio, R, 134
Chang correlation (substitute for Gilliland	minimum reflux ratio, $R_{min}$ 150
correlation), 170, 171, 178	optimum reflux ratio, 152, 153
column diameter, 159–161	reflux ratio optimization
column height, 161	multipliers, m, 153
	maniprovid, III, 100

Distillation (Continued)	final moisture content, 349
relative volatility, 121, 141, 167	free moisture content, 350
geometric mean relative volatility,	rotary dryer flight arrangements, 354
167, 168	rotary dryers, 352-356
sharp separation, 163	rotary dryer unit
side streams, 136	(Manhattan College), 353
stripping section, 119, 135	spray dryers, 361
stripping section operating line	spray dryer unit
(SOL), 145	(Manhattan College), 362
surge volume, 161, 183	
theoretical stage, 141	Economic analysis, 490
total reflux, 149, 150	Eddies
transfer unit, 184	Eddy transfer, 80
tray efficiency, 154	Efficiency
Underwood equations	fractional stage efficiency, 116
(minimum reflux ratio), 169, 177	overall efficiency of bubble-cap tray
weeping, 140, 159	absorbers, 230, 231
Distillation equipment	overall efficiency of trayed distillation
overflow weir, 137	columns, 154, 171-173
packed column distillation, 184, 185	Electrodialysis, 101
partial condenser, 140	Electrophoresis, 486
partial reboiler, 140	Electrostatic attraction, 442
setting the column pressure, 164–167	Deutsch-Anderson equation, 455, 456
shortcut design methods (binary or	Matts-Ohnfeldt equation, 456
multicomponent), 161	particle migration velocity, 455
sieve tray column (single crossflow),	typical precipitation rate parameters for
138, 139	various applications, 455
tray, types of	Electrostatic precipitators (ESPs), 454
bubble-cap tray, 137	Elutriator, 447
sieve tray, 138	Encapsulation, 478
valve tray, 138	Engineering economics, 489
tray, single crossflow	bonds, 496
configuration, 137	break-even point, 495
active area, 139	compound interest, 491
bubbling area, 160	depreciation, 493
net area, 160	fabricated equipment cost index
tray spacing, 182	(FECI), 493
Drag coefficient, 443	incremental cost, 496
for spheres, 444	perpetual life, 494
Drag force, 443	present net worth (PNW), 494
Drying, 347	present worth, 492
constant rate period, 349	profit, 498
drop diameters, 364	rate of return, 495, 496
falling rate period, 349	simple interest, 491
Friedman and Marshall heat transfer	Environmental issues of concern,
coefficient equation, 356	566-568
moisture content	Equilibrium, 37–40
critical moisture content, 348, 349	equilibrium considerations,
equilibrium moisture content, 347	37, 38

Ergun equation, 269	countercurrent flow, 111, 112
Ethics, 549	crossflow, 112, 113
code of ethics, 549	Flux, 74
engineering and environmental	net flux, 75
ethics, 557-559	Foam fractionation, 486
Evaporation (as a novel mass transfer	Freeze crystallization, 484
operation), 485	Freezing point, 41
Extraction, 293	
analytical calculation procedures,	Gas laws
304-309	Boyle's law, 31, 32
Baker equation, 322	Charle's law, 31, 32, 34
Chen equation (number of theoretical	Dalton's law, 35
stages), 324	ideal gas law, 31-35
countercurrent extraction, 296, 309	Gas permeation, 432
crosscurrent extraction, 296, 305	describing equations, 433-435
dissociation extraction, 486	"stage cut" 434
equilibrium data for n-butanol/acetic	Gibb's phase rule, 375
acid/water system at, 30°C, 302	Gravitational constant, $g_c$ , 17
extract, 295	Gravity sedimentation, 467
fractional extraction, 294	circular-basin continuous thickener, 468
Kremser equation, 309	clarification vs. thickening, 467
leaching/lixiviation, 293	hindered settling, 469
liquid-liquid extraction, 294	thickener operating zones, 468
overflow, 316	wall effect, 469
variable vs. constant overflow,	Gravity settlers, 447, See "decanter"
317, 318	• • • •
phase ratio, 297	Heat duty of a condenser, 150, 151
plait point, 300, 301	Heat exchangers
raffinate, 295	dimensions of heat exchanger
solid-liquid extraction, 312	tubes, 614
types of, 313	Heat transfer
solvent selectivity, 298	classic equation for, 393
ternary equilibrium diagram, 300, 301	Henry's law, 187, 200
theoretical stage, 295	High-gradient magnetic separation
underflow, 316	(HGMS), 477
Extraction equipment	Hindered settling, 469
liquid-liquid extraction column	Humidification, 327
(Manhattan College), 297	adiabatic saturation temperature,
multistage devices, 296	329, 333
single stage units, 295, 296, 306	cooling ponds, 343
solid-liquid extraction equipment,	cooling towers, 340–343
315, 316	dew point temperature, T <sub>dp</sub> , 329
313, 310	humid enthalpy, 330
Fahrenheit scale, 20, 21	humid heat capacity, 328
Filtration, 474	humid volume, 328, 330
Flocculation, 474	humidity
Flotation processes, 472	absolute humidity, 327
Flow patterns	molal humidity, 327
cocurrent flow, 109–111	relative humidity, 328
	icium vo munidity, 520

Humidification (Continued)	adsorption, 104
psychrometric chart, 329	crystallization, 392-393
high temperature, 332	distillation, 103, 104
low temperature, 331	extraction, 104-105
saturation curve, 330	humidification and drying, 105
spray columns, 343	Mass transfer operations
wet-bulb temperature, T <sub>wb</sub> , 329	classification of, 97-102
	contact of immiscible phases, 98-101
Ideal gas law, 31–35	direct contact of miscible phases, 102
Ideal stage, See "Theoretical stage"	miscible phases separated by a
Inertial collectors, 447	membrane, 101
Inertial impaction, 442	Maximization/minimization
Ion exchange, 484	first derivative test, 509
	Melting point, 41
Kelvin scale, 20, 21	Membrane separation, 407
Kinetic analysis, 39	desalination (via reverse osmosis), 410
•	electrodialysis, 408
Laminar film, 81	gas permeation, 408, 432
Laminar flow, 28	describing equations, 433–435
Liquid ion exchange (LIE), 484	microfiltration, 407, 427
Liquid-solid equilibrium (LSE), 68, 69.	describing equations, 428-430
See also "Adsorption"	nanofiltration, 407
Logarithmic mean	permeate, 407, 409
logarithmic mean humidity	retentate, 407, 409
difference, 361	reverse osmosis (RO), 407-414
logarithmic mean temperature	describing equations, 414-418
difference, 360	ultrafiltration (UF), 420
Lognormal probability distribution,	describing equations, 421-425
385, 386	Membrane separation equipment
	dialysis membrane, 408
Manometer, 22	reverse osmosis, hollow fine fiber (HFF)
Mass fraction, 24	for, 409, 410
Mass transfer	Microfiltration, 427
macroscopic approach, 8, 10	average transmembrane pressure
microscopic approach, 9	(ATP), 428
molecular approach, 9	describing equations, 428-430
Mass transfer, theories of	Mixing
boundary layer theory, 81	macroscopic, 28
empirical approaches, 81	molecular, 28
surface renewal theory, 81	Mole fraction, 24
two film theory, 81, 82	Molecular diffusion, 8
Mass transfer coefficients, 80	Molecular weight, 23, 24
experimental mass transfer	Moles, 23, 24
coefficients, 90	Momentum, 17
individual mass transfer coefficients,	
81-87	Nonideal solutions, 61-64
overall mass transfer coefficients, 87	Normal boiling point, 41
Mass transfer equipment	Normal probability distribution, 385
absorption 104	Novel senaration processes 483

Numerical methods, 513	Psychrometric chart, 329
differentiation methods, 515-517	definitions of psychrometric terms, 330
finite difference method, 520	high temperature, 332
lumped-parameter method, 521	low temperature, 331
method of least squares, 516	•
Newton-Raphson method, 526-528	Radiation
regression analysis, 515	radiative transfer, 8
Runge-Kutta method, 522-526	Rankine scale, 20, 21
trapezoidal rule, 518-520	Rate considerations, 38, 39, 71
1	Relative volatility, 121
Optimization, 530	Resin adsorption, 485
Osmosis	Reverse osmosis (RO), 407-414
osmotic pressure, 412	describing equations, 414–418
	Van't Hoff equation, 414
Partial differential equations, 529	Reynolds number, 28, 29
Particulate matter, 10 (PM10), 440	Risk assessment
Particulate matter, 2.5 (PM2.5), 440	cost/protection analysis, 581
pH, 29, 30	hazard analysis (HAZAN), 585
Phase diagram, 41	hazard and operability study (HAZOP),
eutectic point, 373	584, 585
isothermal invariant point, 376	hazard risk assessment, 571–574
lever rule, 376	health risk assessment, 568–571
	Health fisk assessment, 308–371
plait point, 300, 301 ternary equilibrium diagram, 300, 301	Scientific notation 17 19
	Scientific notation, 17, 18
two component solid-liquid system, 373	Screen mesh, 382, 383
Phase equilibrium, 41	Screen scales, Tyler and US
Gibbs phase rule, 44, 45	Standard, 383
Phase separation vs. component separation	Semi-batch operation, 108
processes, 483	Significant figures, 17, 18
Piping	Simpson's, 3-point rule, 128
dimensions, capacities and weights of	Solidification, 477
standard steel pipes, 612, 613	Stagewise operation, 116
Poise, 25	Standard conditions
Pressure, 22, 23	standard vs. actual conditions, 33–35
interfacial partial pressure, 82	STP, 32, 33
vapor pressure, 31	Standard deviation (sample), 384
Process variables, 19	State function, 151
Properties	Steady state, 108
intensive vs. extensive, 20	Steam tables, 616-622
of air at, 1 atm, 611	Steel pickling, 212
of selected gases at, 1 atm and, 20°C	Stoke's law, 443
(68°F), 607	Stripping, 235
of selected liquids at, 1 atm and, 20°C	key equations for stripping calculation,
(68°F), 608, 609	242, 243
of water at, 1atm, 610	number of transfer units (NTU), 240
physical vs. chemical, 19	removal efficiency, 240
saturated steam tables, 616-618	stripping of an EO-water system, 238
saturated steam-ice tables, 622	Stripping column, 103, 137
superheated steam tables, 619-621	Sublimation, 99

Temperature, 20	P-x,y diagram
Temperature scales, 20, 21	methanol-water system at, 40°C
Theoretical stage, 110, 111, 141	(Raoult's law), 52
Transient operation, See "Unsteady state"	Raoult's law, 45-53
Transport phenomena, 7	modified Raoult's law, 61
transport equations, 9	Raoult's law vs. Henry's Law,
transport phenomena approach, 9	59-61
Triple point, 42	T-x,y diagram
Turbulent flow, 28	ethanol-water system at, 1 atm, 51
	x,y diagram
Ultrafiltration, 420	methanol-water system at, 40°C
concentration polarization, 423	(Raoult's law), 53
describing equations, 421–425	Vapor–solid equilibrium (VSE)
gel formation, 423	adsorbent capacity, 65
Unit conversion, 15, 16	adsorption equilibrium, 64
Unit operations	BET isotherm, 66
definition of, 5	Freundlich isotherm, 65, 66
unit operations approach, 7	Langmuir isotherm, 66
unit operations concept, 4, 5	Polanyi potential theory, 66, 67
Units, 11–14	vapor/solid equilibrium isotherms
abbreviations, selected common,	carbon dioxide on molecular
603, 604	sieves, 252
conversion factors, 15, 16	carbon tetrachloride on activated
conversion factors, common	carbon, 65
engineering, 606	selected hydrocarbons on activated
English engineering units, 11, 13	carbon, 251
prefixes, 14	Venturi scrubber, 457
SI units, 11, 13	gas velocity, typical values for, 458
SI conversion constants, 599–602	Johnstone collection efficiency
SI multiples and prefixes, 599	equation, 457
Universal gas constant, R, 32, 33	Nukiyama – Tanasawa relationship,
Unsteady state, 108	458
Chistedly state, 100	overall efficiency of N scrubbers
Vacuum, 22	in parallel, 458, 459
Vapor, 42	Vibrating screens (as a novel mass
Vapor pressure, 31	transfer operation), 487
Antoine equation, 47–49	Viscosity
coefficients of selected substances, 48	absolute viscosity, 25, 26
Clapeyron equation, 47, 48	of air, 26
coefficients of selected substances, 47	of water, 26
Vapor-liquid equilibrium (VLE)	kinematic viscosity, 25, 26
Henry's law, 45, 53~59	Saybolt seconds, 26
Henry's law constants for gases in	Saybolt universal viscometer, 26
water, 55	Volume fraction, 24
	<b></b>