Cambridge University Press
978-0-521-89573-6 - Separation of Molecules, Macromolecules and Particles: Principles, Phenomena and Processes
Kamalesh K. Sirkar
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Separation of Molecules, Macromolecules and Particles

Providing chemical engineering undergraduate and graduate students with a basic understanding of how the separation of a mixture of molecules, macromolecules or particles is achieved, this textbook is a comprehensive introduction to the engineering science of separation.

- Students learn how to apply their knowledge to determine the separation achieved in a given device or process.
- Real-world examples are taken from biotechnology, chemical, food, petrochemical, pharmaceutical and pollution control industries.
- Worked examples, elementary separator designs and chapter-end problems give students a practical understanding of separation.

The textbook systematically develops different separation processes by considering the forces causing the separation, and how this separation is influenced by the patterns of bulk flow in the separation device. Readers will be able to take this knowledge and apply it to their own future studies and research in separation and purification.

Kamalesh K. Sirkar is a Distinguished Professor of Chemical Engineering and the Foundation Professor of Membrane Separations at New Jersey Institute of Technology (NJIT). His research areas are membranes and novel membrane based processes.

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"The first comprehensive book that takes the fundamentals of separation on a molecular level as the starting point! The benefit of this approach is that it gives you a thorough insight in the mechanisms of separation, regardless of which separation is considered. This makes it remarkably easy to understand any separation process, and not only the classical ones. This textbook finally brings the walls down that divide separation processes in classical and non-classical."

Bart Van der Bruggen, University of Leuven, Belgium

"This strong text organizes separation processes as batch vs continuous and as staged vs differential. It sensibly includes coupled separation and chemical reaction. Supported by strong examples and problems, this non-conventional organization reinforces the more conventional picture of unit operations."

Ed Cussler, University of Minnesota

"This book fills the need by providing a very comprehensive approach to separation phenomena for both traditional and emerging fields. It is effectively organized and presents separations in a unique manner. This book presents the principles of a wide spectrum of separations from classical distillation to modern field-induced methods in a unifying way. This is an excellent book for academic use and as a professional resource."

C. Stewart Slater, Rowan University

"This book is an excellent resource for the topic of chemical separations. The text starts by using examples to clarify concepts. Then throughout the text, examples from many different technology areas and separation approaches are given. The book is framed around various fundamental approaches to chemical separations. This allows one to use this knowledge for both current and future needs."

Richard D. Noble, University of Colorado

"This book provides a unique and in depth coverage of separation processes. It is an essential reference for the practicing engineer. Unlike more conventional textbooks that focus on rate and equilibrium based separations, Prof Sirkar focuses on how a given separation takes place and how this is used in practical separation devices. Thus the book is not limited by application e.g. chemical or petrochemical separations.

"As chemical engineering becomes increasingly multidisciplinary, where the basic principles of separations are applied to new frontier areas, the book will become an essential guide for practitioners as well as students.

"The unique layout of the text book allows the instructor to tailor the content covered to a particular course. Undergraduate courses will benefit from the comprehensive and systematic coverage of the basics of separation processes. Whether the focus of a graduate course is traditional chemical separations, bioseparations, or separation processes for production of renewable resources the book is an essential text."

Ranil Wickramasinghe, University of Arkansas

"This advanced textbook provides students and professionals with a unique and thought-provoking approach to learning separation principles and processes. Prof. Sirkar has leveraged his years of experience as a separation scientist and membrane separation specialist, to provide the reader with a clearly written textbook full of multiple examples pulled from all applications of separations, including contemporary bioseparations. Compared to other separations textbooks, Prof. Sirkar's textbook is holistically different in its approach to teaching separations, yet provides the reader with a rich learning experience. Chemical engineering students and practicing professionals will find much to learn by reading this textbook."

Daniel Lepek, The Cooper Union

Separation of Molecules, Macromolecules and Particles

Principles, Phenomena and Processes

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Preface

This is an introductory textbook for studying separation. Primarily, this book covers the separation of mixtures of molecules; in addition, it provides a significant treatment of particle separation methods. Separation of macromolecules has also received some attention. The treatment and coverage of topics are suitable for chemical engineering students at undergraduate and graduate levels. There is enough material here to cover a variety of introductory courses on separation processes at different levels.

This book is focused on developing a basic understanding of how separation takes place, and of how the resulting separation phenomenon is utilized in a separation device. The role of various forces driving molecules or particles from a feed mixture into separate phases/fractions/regions is basic to such an approach to studying separation. The separation achieved is then amplified in an open separator via different patterns of bulk-phase velocities vis-à-vis the direction(s) of the force(s). The forces are generated by chemical potential gradient, electrical field, rotational motion, gravity, magnetic field, etc. The resulting separation is studied under three broad categories of separation processes.

Separation processes driven by a negative chemical potential gradient are generally multiphase systems and are treated under the broad category of phase equilibrium driven processes. External force driven processes populate the second category, and include those operating under an electrical field, rotational motion, magnetic field or gravity; thermal diffusion processes are also briefly included here. The third category of membrane based processes studied is driven generally by a negative chemical potential gradient; however, electrical force is also relevant for some processes. The treatment of any external force driven processes will cover both separation of molecules and particle separations.

These physical separation methods are often reinforced by chemical reactions, which are usually reversible. An elementary treatment of the role of chemical reactions in enhancing separation across a broad spectrum of phase equilibrium driven processes and membrane based processes has been included. The level of treatment in this book assumes familiarity with elementary principles of chemical engineering thermodynamics and traditional undergraduate levels of knowledge of ordinary differential equations and elementary partial differential equations.

Specific aspects of a given separation process are studied in the chapter devoted to those aspects for all separation processes. To study a particular separation process in great detail, one therefore has to go to different chapters. The footprints of a given separation process are provided at the beginning of the book (Tables 1–7); there are quite a few tables to cover a variety of separation processes. The list of processes is large; however, it is far from being all inclusive. The introductory chapter, which provides additional details about various chapters, as well as about the book, is preceded by a notation section. All references appear at the end of the book.

The description of the extent of separation achieved in a closed vessel for a mixture of molecules is treated in Chapter 1. Chapter 2 illustrates how to describe the separation of molecules in open separators under steady and unsteady state operation; a description of separation for a size-distributed system of particles is also included. Chapter 3 introduces various forces developing species-specific velocities, fluxes and mass-transfer coefficients, and illustrates how the spatial variation of the potential of the force field can develop multicomponent separation ability. The criteria for chemical equilibrium are then specified for different types of multiphase separation systems, followed by an illustration of integrated flux expressions for two-phase and membrane based systems.

Chapter 4 develops the extent of separation achieved in a closed vessel to a variety of individual processes under each of the three broad categories of separation processes. Chapter 5 demonstrates how separation can be considerably enhanced by chemical reactions in phase equilibrium based and membrane based processes under both equilibrium- and rate-controlled conditions. For open separators having bulk flow in and out, including continuous stirred tank separators (CSTSs), Chapter 6 provides first the equations of change for molecular species concentration in single-phase and two-phase systems, the trajectory equation for a particle in a fluid and the general equation of change for a particle population. Chapter 6 then treats individual separation processes under each of the three

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broad categories of separation processes when the bulk flow is parallel to the direction of the force and in CSTS mode.

Chapter 7 follows this latter approach of treating individual separation processes under each of the three broad categories of separation processes when the bulk flow of feed-containing phase is perpendicular to the direction of the force. Chapter 8 follows the same approach when the bulk flows of two phases/regions in the separator are perpendicular to the direction(s) of the force(s). Chapter 9 briefly elaborates on cascades, which were already introduced in the countercurrent multistaged flow systems of Chapter 8. Chapter 10 introduces the energy required for a number of separation processes. Chapter 11 illustrates a few common separation sequences in a number of common industries involved in bioseparations, water treatment, chemical and petrochemical separations and hydrometallurgy. Conversion factors between various systems of units are provided in an Appendix.

Virtually all separation processes taught to chemical engineering students in a variety of courses have been covered via the approach illustrated in Chapters 3, 4, 6, 7 and 8; in addition, many particle separation methods have been treated. The structural similarity in the separation method between apparently unrelated separation processes becomes quite clear. A few basic principles equip the students with the capability to understand a wide variety of separation processes and techniques, including emerging ones. To aid the student, there are 118 worked examples, 300 problems, 340 figures, 100 tables and 1011 references. A website will provide guidance for computer simulations for a few selected problems.

The introductory chapter provides references to articles and books which influenced the development of various aspects of this book. I have benefitted considerably from the comments on selected chapters of the book by reviewers, anonymous or otherwise. Comments by Professors C. Stewart Slater, of Rowan University, Steven Cramer, of Rensselaer Polytechnic Institute, and Ranil Wickramasinghe, of Colorado State University (now at University of Arkansas), were particularly useful.

Many doctoral students and postdoctoral fellows were of invaluable help during the long gestation period of this book, either in formulating solutions of the problems or in developing illustrative drawings. I want to mention in particular Amit Sengupta, Theoharris Papadopoulos, Xiao-Ping Dai, Meredith Feins, Dimitrios Zarkadas, Quixi Fan, Praveen Kosaraju, Fei He, Atsawin Thongsukmak, Sagar Roy, Dhananjay Singh, John Tang and John Chau. The first two students helped me when we were at Stevens Institute of Technology. Sarah Matthews of Cambridge University Press patiently provided manuscript preparation guidelines and encouraging comments during an ever-shifting timetable. Irene Pizzie did an extraordinary job as the copy editor. Brenda Arthur of New Jersey Institute of Technology tirelessly typed the draft of the whole manuscript over a considerable length of time, while carrying out many other duties.

I must also mention at the end my wife, Keka, without whose patience, help and understanding this book would never have been finished.

Notation

Equation numbers identify where the symbols have been introduced or defined.

The following styles have been adopted.

Bold	vector quantity

Overlines

—	quantity averaged over time or a specific coordinate direction, multicomponent system, Laplace transformed dependent variable
— =	averaged quantity
^	quantity in a mixture, per unit mass of bulk phase

Underlines

_	hypothetical binary system quantity (2.4.23), (2.4.24)
~, =	vector quantity, tensor quantity

Brackets

$\langle v_{tj} \rangle$	average value of v_{tj} over surface area $\boldsymbol{S}_j$

a	ellipsoid semiaxis dimension; see also (3.1.10a); constant in relations (3.1.49), (4.3.7) and (4.3.43a); interfacial area per unit volume, defined by (7.2.191), (7.3.25)
a_1; a_2, a_3,...	constant in (3.3.105), (4.1.42b), (4.3.29) and (5.2.147); constants in (7.2.73), (7.3.50) and (7.3.139)
a_1	constant in (7.2.198a)
a_A	stoichiometric coefficient for species A
a_H	Hamaker constant (3.1.16)
a_i; $\mathrm{a}_i(T)$; a_{ij}, $a_{i\mathrm{l}}$; $\hat{\mathrm{a}}_i$; a'_m; $a_{\mathrm{ms}\ell}$	activity of species i; equilibrium constant (7.1.63); atom fraction of ith isotope of an element in region j (1.3.6), value of a_i in region j and liquid phase, respectively; amplitude (7.1.72b); constant in (4.3.43c); membrane surface per unit channel length (7.2.70)
a_p	surface area of a particle
a_{s1}, a_{s2}; a_{sw}	activity of solvent s in regions 1 and 2, respectively; activity of salt in water
a_{sp}	pore surface area per unit volume of the porous medium of porosity ε
a_v, a_{vc}	surface area of a particle per unit particle volume, value of a_v in a cake (6.3.135j)
$a_\pm$	mean electrolyte activity (3.3.119d)
A; A_1, A_2, A_3	amplitude (7.3.18), pure-water permeability constant in reverse osmosis and diffusive ultrafiltration; constants in (7.1.90b), three surface areas in control volume of Figure 7.2.6(b)
$A(\mathrm{r})$	cross-sectional area of a cone in centrifugal elutriation
A_c	cross-sectional area of duct
A_hex; A_{ij}; A_m; A^t_m; $A_i(T)$; A^o_i	heat exchanger surface area; constant in equations for activity coefficients (4.1.34d); surface area of membrane; total membrane surface area; modified equilibrium constant (7.1.66); constant (7.1.72b)
$A_{1\rho}$	constant in crystal growth rate equation (6.4.27)
A_p	projected area of a particle (3.1.64); transport coefficient in solution-diffusion-imperfection model (3.4.60a)
$A^+_p(\mathrm{x})$	cumulative crystal surface area distribution fraction (6.4.17)
A_T	total particle surface area per unit volume of total mixture (Example 2.4.2); total crystal surface area per unit liquid volume (6.4.16)
Am^+, Am^-, $\mathrm{Am}^\pm$	three forms of amino acid
b	ellipsoid semiaxis dimension; proportionality constant in osmotic pressure relation (3.4.61b); half of channel gap; width of region of gas flow completely cleaned up by a fiber (6.3.42a); constant in crystal growth rate expression (6.4.35); parameter (7.2.18); liquid envelope radius (7.2.208)

b_1, b_2, b_3	constants in relations (3.1.143f)
b_1	constant in (3.3.105), (5.2.147)
b_f; b_i; b_if; $\mathrm{b}_{\mathrm{i}\ell}$; b_1^i	membrane feed channel height (Figure 7.2.3(a)); constant in equilibrium relation (3.3.81); constant in (7.1.73), constant in Freundlich isotherm (3.3.112c); constant in Langmuir isotherm (3.3.112a); constant in equation (4.1.42a)
b'_{i-k}, b'_k	proportionality constant in (5.2.154), equilibrium constant in (5.2.155)
b_m, b'_m	constants in (4.3.43a,c)
$\boldsymbol{B}$	magnetic induction vector (3.1.19)
B; B^o; B_i^o;B_p	constant, density function of the birth rate of new particles (6.2.50g), value of B as $r_p \to 0$; value of B^o for crystal growth rate gr_i; duct perimeter (7.3.41)
Bi	Biot number (3.4.35)
B_1p, B_2p	second virial coefficients for interaction between polymers 1 and 2 (4.1.34p)
c; c_C	velocity of light; gap between plates at entrance (Figure 7.3.10), stoichiometric coefficient for species C
C	clearance of a solute (8.1.390)
C_1,C_2; $C_2(x)$	integration constants (3.3.10b); molar concentration of species 2 at location x
C_2f	molar concentration of species 2 in initial mixture, mol/liter
$\mathrm{C}^{(2)}$	defined in (6.3.75)
C_A^0, C_A^δ	molar concentration of A at $z = 0$, δ (3.1.124)
$C_{\mathrm{A}\ell b}$, $C_{\mathrm{A}\ell i}$	molar concentration of A in phase bulk and phase interface and in liquid at gas–liquid interface (3.4.1b)
$C_{\mathrm{A}wb}$, $C_{\mathrm{A}wi}$; $C'_{\mathrm{A}wb}$	molar concentration of A in bulk water and in water at phase interface (3.4.45e); critical value of $C_{\mathrm{A}wb}$ for maximum enhancement (5.3.53)
$C_{\mathrm{B}ob}$, $C_{\mathrm{B}oi}$	molar concentration of species B in organic-phase bulk and interface, respectively
C_c; $C'_{\mathrm{C}b}$;C_D	slip (Cunningham) correction factor (3.1.215); critical value of bulk concentration of C for maximum enhancement (5.3.29b); particle drag coefficient (3.1.64), (6.3.4)
C_{FC}	molar concentration of fixed charges in ion exchange resin
C'_H1, C'_H2	dual mode sorption constants for species 1 and 2 (3.3.82a,b)
C_i; $\overline{C}_i$; C_i^t; C_i^*; C_{ig}^*; C_{i1}^i, C_{i2}^i	molar concentration of species i; an average of the molar concentration of species i in the feed and the permeate (5.4.74), (6.3.158b); total molar concentration of species i in the porous medium per unit volume (3.1.118b); nondimensional species i concentration (5.3.35j), hypothetical gas-phase species i concentration (8.1.47); initial bed concentration of solute i in phases 1 and 2
C_{i10}, C_{i20}	values of C_{i1}, C_{i2} at $z = 0$
$C_i^o(\pi)$	liquid-phase concentration of pure solute i at spreading pressure π and temperature T providing the same surface phase concentration of i as the mixture
$C_{i\mathrm{gel}}$	molar species i concentration in gel
C_{ij}	molar concentration of species i in region j or location j or stream j; $j = b$, bulk; $j = E$, extract; $j = f$, feed region; $j = g$, gas phase; $j = k$, kth phase; $j = \ell$, liquid; $j = \ell'$, adhering liquid phase on crystal; $j = m$, membrane; $j = o$, organic; $j = p$, permeate, product; $j = r$, raffinate; $j = R$, ion exchange resin phase, raffinate; $j = s$, solution, solid phase or pore surface; $j = w$, water, mol/liter
C_{ij}^t; C_{ijn}	total molar concentration of species i in region j including complexed or dissociated forms; value of C_{ij} on nth plate/stage
C_{ij}^0, C_{ij}^ℓ, C_{ij}^δ	species i concentrations in phase j at locations 0 (or initial concentration), ℓ and δ
$C_{i\ell b}$, $C_{i\ell e}$, $C_{i\ell i}$	molar concentrations of species i in bulk solution, at the end of concentration process and at the beginning of concentration process (6.3.173)
C'_{ig}, C'_{igf}	molar species i concentration per unit gas phase volume in a pore
$\overline{C}_{ik}$, $\overline{\overline{C}}_{ik}$, $\hat{C}_{ik}$; $\overline{C}_{it}$	intrinsic phase average, phase average and deviation in C_{ik} for species i concentration in phase k (6.2.24a,b), (6.2.28); defined by (7.1.94)
C_{im}^d, C_{im}^H; C_{im}^p	species i concentration in membrane: for Henry's law and Langmuir species, respectively, in dual sorption model (3.3.81); membrane pore liquid
C_{imi},C_{imo},C_{iob}, C_{iwi}, C_{iwb}	molar concentrations of species i at various locations in Figure 3.4.11
C_{pR}, C_{pw}	molar protein concentrations in resin phase and aqueous solution

C_{sf}, C_{sm}, C_{sp}	molar solvent concentration in feed, membrane and permeate, respectively
C_t; C_{tj}; C_{vp}	total molar concentration; C_t in a mixture in region j; volume of particles per unit fluid volume (7.2.176)
d; d_h; d_i; $d_{\ell m}$	diameter of tube/pipe/vessel; hydraulic diameter (Table 3.1.8); effective diameter of a molecule of gas species i (3.3.90a); logarithmic mean diameter (8.1.417)
$\mathbf{d}_i$; d_{gr}; d_{imp}	force-type term (3.1.178), (3.1.181); grain diameter; diameter of an impeller
d_{ion}; d_p; d_w; d_{p1}, d_{p2}	mean diameter of a molecular ion; mean diameter of a particle (6.1.4b); wire diameter (3.1.23); diameters of particles 1 and 2
d_{32}	Sauter mean diameter of a drop or particle (6.4.88), (6.4.89)
D	diffusion coefficient of species in countertransport through liquid membrane
D_{A}, D_{C}; D_{B}	diffusion coefficient of species A and C, respectively; dialysance in hemodialysis (8.1.389)
D_{eff}	effective diffusion coefficient (5.4.64a)
D_{gr}	crystal growth diffusivity (6.4.45)
D_p; $D_p(\phi)$	diffusion coefficient for particle (3.1.68), (6.2.52); shear-induced particle diffusivity (3.1.74), (7.2.126), (7.2.131a)
D_r	desalination ratio (1.4.25), (2.2.1a)
$D_{i,\text{eff}}$; $D_{i,\text{eff},r}$, $D_{i,\text{eff},z}$; $D_{i,\text{eff},1}$	effective diffusion coefficient of i in liquid (6.2.18), (6.3.16b); value of $D_{i,\text{eff}}$ in r-and z-directions; value of $D_{i,\text{eff}}$ in phase/region 1
$D_{i,\text{eff},k}$; $\underline{\underline{D}}_{i,\text{eff},k}$	effective diffusion coefficient of i in phase k (6.2.33); dispersion tensor (6.2.31)
D_{ij}; D_{il}; D_{is}	diffusion coefficient of species i in region j; j = l, liquid; $j = s$, solvent
D_{A}^{T}, D_{B}^{T}; D_{is}^{T}	thermal diffusion coefficient for species A and B (3.1.44); for species i in solution
D_{AB}; D_{BR}	binary diffusion coefficient for mixture of gases A and B; diffusion coefficient of particles due to Brownian motion (7.2.216)
D_{iD}, D_{iH}	diffusion coefficients in dual sorption–dual transport model (3.4.78)
D_{ie}	effective diffusion coefficient of i in a porous medium (3.1.112d)

D_{im}; D_{imo}; D_{ip}	diffusion coefficient of i in membrane (6.3.149); value of D_{im} for $C_{im} = 0$ (3.4.67b), D_i in a pore (3.4.89c), (6.3.145a); effective D_i in the pores of a particle
$\overline{D}_{ik}$, $\overline{D}_{im}$	multicomponent diffusion coefficient of species pair (i, k) and (i, m) in Maxwell–Stefan approach
D_{iK}	Knudsen diffusion coefficient for species i (3.1.115c)
D_{iM}	effective binary diffusivity of species i in a mixture (3.1.184), (3.1.185)
D_{is}; D_{is}^0; D_{is}^N	binary diffusion coefficient for solute i/solvent s; value of D_{is} at infinite dilution; Nernst–Planck binary diffusion coefficient for species i/solvent s
D_{12}	binary diffusion coefficient for species 1 and 2
De; $(De)_{mv}$	density function of particles which disappear (die) (6.2.50h); see (7.2.170a) and (7.2.172)
Df; DF	decontamination factor (2.2.1c); dilution factor (6.4.106), (7.2.91c)
e	charge of an electron, 1.60210 × 10^{-19} coulomb
e_i	constant in adsorption isotherm for solute i (3.3.113d)
en_b,en_M,en_{MN}, en_{MP},en_p	molecular energy in the bulk, due to intramolecular interactions, due to intermolecular interactions, due to interaction between molecules and pores and total energy for molecules in the pore (3.3.89d)
$\boldsymbol{E}$; E; E_c; E_{D_i}; E_e	electrical force field; its magnitude (3.1.8), (6.1.22), (6.3.8f), extraction factor (8.1.281), stage efficiency (6.4.72); electrical field strength E_c (7.3.32a); activation energy for diffusion of species i in polymer (4.3.46b); extraction factor for extraction section (8.1.303)
E_i; E_o; E_{oG}; E_s; E_y; E_{BRS}, E_{GrS}	enrichment of species i by pervaporation (6.3.193b), particle collection efficiency (7.2.200b); overall column efficiency (8.1.195); point efficiency (8.3.13); extraction factor for the scrubbing section; electrical field strength in y-direction (7.3.48); particle collection efficiency (7.2.219), (7.2.214)
E_{IS}; E_{IS}	inertial impaction based single fiber capture efficiency (6.3.42a); particle capture efficiency by interception (7.2.224)

E_{ME}, E_{MR}; E_{MV}; E_N	Murphree extract stage efficiency, Murphree raffinate stage efficiency (6.4.70), (6.4.71); Murphree vapor efficiency (8.1.198); Newton particle separation efficiency (2.4.14a)
E_T; E_T^1; E_{T_i}	total efficiency in solid–fluid separation (2.4.4a), overall filter efficiency (6.3.45), (7.2.201); reduced efficiency of Kelsall (2.4.16a); E_T for *i*th solid–fluid separator (2.4.17c,d)
f	friction factor (6.1.3a), fractional consumption of chemical adsorbent (5.2.19d)
f_2	fraction of the solute in ionized form ($i = 2$) in RO (5.4.4)
$f(r)$; $f(r_p)$; $f(\varepsilon)$	molar density function in a continuous/semi-continuous mixture with characteristic property r; particle size probability density function (2.4.1a), pore size distribution function in a membrane; defined by (7.2.222a,c)
$f_f(r_p)$, $f_1(r_p)$, $f_2(r_p)$	value of $f(r_p)$ for feed stream, overflow and underflow based on particle weight fraction in a given size range (2.4.1b)
f_A, f_i; f_i^0	fugacity of species A, species i; standard state fugacity of species i
$f_g(\text{gr})$	probability density function of crystal growth rate (6.4.41a)
f_{il}	fugacity of pure species i in liquid phase
f_m, f'_m	quantities characteristic of a membrane polymer (4.3.46a,d)
$f_{ij}^0, f_{ig}^0, f_{il}^0$	standard state fugacity of species i in region j; $j = g$, gas phase; $j = \ell$, liquid phase
f_i^d, f_p^d	frictional coefficient for species i and spherical particle
$\hat{f}_{ig}, \hat{f}_{ij}, \hat{f}_{il}; \hat{f}_{ijpl}$	value of fugacity of i in a mixture in gas phase, phase j and liquid phase, respectively; value of $\hat{f}_{ij}$ for a planar surface
f_{io}^d	value of f_i^d for a sphere of equivalent volume (3.1.91e)
f_{im}^d, f_{sm}^d	frictional coefficient for solute i and solvent s in a membrane
$f_f(M), f_l(M), f_v(M)$; f_∞, f_λ	value of $f(r)$, where $r = M$, molecular weight, for the feed mixture, liquid fraction and the vapor fraction, respectively; defined by (7.1.59a), (7.2.187), respectively
f_M; f_{Qm}, f_{yo}	fraction of the total metal ion concentration in the aqueous phase present as M^{n+} (5.2.97); probability density functions (7.3.79), (7.3.80)
$\boldsymbol{F}$; $\hat{\boldsymbol{F}}$, $\hat{\boldsymbol{F}}_p$; F	force on a particle; value of $\boldsymbol{F}$ per unit particle mass; degrees of freedom (4.1.22)
$F(r_p)$	probability distribution function corresponding to $f(r_p)$ (2.4.1c), crystal size distribution function (6.4.11)
$\boldsymbol{F}_i$; F_i^{ext}	electrostatic force on 1 gmol of a charged species in solution (6.3.8a); magnitude of external force on 1 gmol of species i
$F_{\text{acr}x}$	acoustic radiation force in x-direction (3.1.48)
$\boldsymbol{F}_{\text{rad}}$	radiation pressure force (3.1.47), (7.3.267)
$\boldsymbol{F}^{\text{BR}}$	force on very small particle due to random Brownian motion (3.1.43)
$\boldsymbol{F}_{\text{i}}^{\text{ELK}}$	electrokinetic force on particle in double layer (3.1.17)
$\boldsymbol{F}_i^{\text{ELS}}$	electrostatic force on particle i, Coulomb's law (3.1.15)
$\boldsymbol{F}_{\text{i}}^{\text{Lret}}$	London attraction force (3.1.16)
$\boldsymbol{F}_k^{\text{m}}$	force on species k in mass flux $\boldsymbol{j}_i$, force relation (3.1.202)
$\boldsymbol{F}_{\text{net}}^{\text{ext}}$	net external force; for gravity see (3.1.5)
$\boldsymbol{F}_p^{\text{drag}}; \boldsymbol{F}_p^{\text{iner}}; F_{pz}^{\text{ext}}$	frictional force on a particle; inertial force on a particle (6.2.45); external force on a particle in z-direction
$\boldsymbol{F}_{ti}, \boldsymbol{F}_{ti}^{\text{ext}}$	total force and total external force on 1 gmol of species i (3.1.50)
$\boldsymbol{F}_{tp}^{\text{ext}}; F_{tpx}^{\text{ext}}, \boldsymbol{F}_{tpy}^{\text{ext}}; F_{tpz}^{ext}$	total external force on a particle (3.1.59), (6.2.45); components of F_{tp}^{ext} in x-, y-and z-directions
$\boldsymbol{F}_{\text{TA}}$	force on 1 gmol of species A due to a temperature gradient (3.1.44)
$\mathcal{F}$	Faraday's constant, 96 485 coulomb/gm-equivalent
g; g_c; g_m	acceleration due to gravity; conversion factor; a quantity characteristic of a membrane polymer (4.3.46a)
$\boldsymbol{g}^{\text{ext}}; g_x^{\text{ext}}, g_y^{\text{ext}}, \text{g}_\text{z}^{\text{ext}}$	external body force per unit mass; its components in x-, y-and z-directions
gr_i	intrinsic growth rate of *i*th crystal (6.4.41a)
G; G_g	superficial mass average velocity based on empty flow cross section, G for gas phase
G; G_a, G_b; G_i; G_o	growth rate of crystal (6.4.25), (6.4.3b); value of G under condition a, condition b; factor representing contribution of species i properties to Q_{im} (4.3.56a); constant

$\overline{G_c}$; $\overline{G_{Dr}}$; $\overline{\mathrm{G}}_{\mathrm{D}\mu}$	convective hindrance factor (3.1.113); drag factor reducing solute diffusion by hindrance (3.1.112e); function of particle volume fraction in hindered settling (4.2.61)
$\overline{G_i}$;$\overline{G_{ij}}$	partial molar Gibbs free energy of species *i*, ratio of solute *i* velocity to the averaged pore solvent velocity, convective hindrance factor (=$\overline{G}_c$) (3.1.113), (3.4.89b); value of $\overline{G_i}$ in region *j*
$G_r(r_p)$	grade efficiency function (2.4.4b)
G_{tj}; G_{crit}	total Gibbs free energy of all molecules in region *j* (3.3.1), (4.2.23); defined by (7.1.58e)
Gr; $Gr(\beta_r, \sigma_v)$; Gz	Grashof number (3.1.143e); function defined by (7.2.174); Graetz number (8.1.276)
h; h_{o}	membrane flow channel height, distance between particle and collector (3.1.17), constant in (4.1.9a) for Henry's law constant, $(1/h)$ is a characteristic thickness of double layer (6.3.31a), height of liquid in a capillary at any time *t*; value of *h* as $t \to \infty$ (6.1.11)
h_+, h_-, h_G	contributions of different species to *h* (4.1.9c)
$h_{\min}$	minimum value of *h*
H; H_f; H_i; H_i^C, $[\mathrm{H}_\mathrm{i}^C]'^{\prime}$; H_i^P; H_{lf}, H_{vf}	plate height, stack height; molar enthalpy of feed; value of *H* for species *i* (6.3.22), Henry's law constants for species *i* in gas–liquid equilibrium; (3.3.59) (4.1.7); (3.4.1b), (5.2.6); (5.2.7); (8.1.49), (3.4.1a); molar enthalpy of liquid fraction and vapor fraction, respectively, of the feed
$H_{o\ell}$, $H_{o\ell P}$	height of a transfer unit defined by (8.1.96)
$\mathbf{H}^{\mathrm{m}}$	magnetic field strength vector
H_{A}, $H_{\mathrm{A}}^{\mathrm{o}}$, $H_{\mathrm{A}}^{\mathrm{c}}$; H_1, H_2	Henry's law constants for species A (3.4.1a,b), (3.4.8); defined by (7.1.20b)
H_{D}, H_{M}, H_{S}, H_{SM}	components of plate height (7.1.107e–i)
$\overline{H}_i$	partial molar enthalpy of species *i*
HTU	height of a transfer unit (6.4.85), (8.1.54b), (8.1.57b), (8.1.65e), (8.1.245b), (8.1.247a), (8.1.357b)
$\mathbf{i}$	unit vector in positive *x*-direction, current density (3.1.108c)
I; $\boldsymbol{I}$; I_j; $I(C_{isbL}^+)$	ionic strength of the solution (3.1.10c), (4.1.9b); purity index (1.4.3b), current; value of purity index for region *j* (1.4.3b); integral (7.2.86)
$\mathbf{j}$	unit vector in positive *y*-direction
$\boldsymbol{j}_i$; j_{ix}, j_{iy}, j_{iz}	mass flux vector of species *i*, $M_i\boldsymbol{J}_i$ (3.1.98), Tables 3.1.3A, 3.1.3B, (6.2.5n); components of $\boldsymbol{j}_i$ in *x*-, *y*- and *z*-directions
J_D	factor defined by (3.1.143g)
$\boldsymbol{J}_i$, J_i^*; $(J_i)_k$; J_1, J_1^{T}	molar flux vector of species *i* (3.1.98), (3.1.99), Tables 3.1.3A, 3.1.3B; value of $\boldsymbol{J}_i$ in region *k*; diffusive molar flux vector of species 1 (4.2.63); temperature gradient driven molar flux vector of species 1 (4.2.62)
J_{iz}, J_{sz}; J_{iy}^*	*z*-components of flux vectors $\boldsymbol{J}_i$ and $\boldsymbol{J}_s$; *y*-component of flux vector J_i^*
J_{iz}^*, J_{jz}^*, J_{sz}^*, J_{Az}^*	*z*-components of flux vectors J_i^*, J_j^*, J_s^* and J_A^*
J_{Ay}^{*t}	total molar flux of species A in *y*-direction (5.4.51)
J_{vz}	volume flux through membrane in *z*-direction (3.4.60c), (6.3.155a)
$\mathbf{k}$; k	unit vector in positive *z*-direction; region or phase, constant in (2.2.8a–c), $(2\pi/\lambda)$ (3.1.48)
k^{B}	Boltzmann's constant (3.1.72), (3.3.90c)
k_a, k_d	rate constants for adsorption and dissociation, respectively (4.1.77a)
k_b, k_f	backward and forward reaction rate constants (5.4.42)
k_{Ao},k_{Aw}	mass-transfer coefficient of species A in organic or water phase
k_c, k_g, k_{xj}, k_y	mass-transfer coefficients for species *i* (3.1.139), (3.4.3)
k_{c}', k_{g}', k_{x}', k_{y}'	values of k_c, k_g, k_x and k_y for equimolar counterdiffusion (3.1.124)
k_d, k_s; k_ℓ,	mass-transfer coefficients in crystallization (3.4.23a,b); liquid film mass transfer coefficient (5.3.3)
k_{igc}, k_{igx}, k_{igy}	mass-transfer coefficients for species *i* in gas phase when the concentration gradient is expressed in terms of *C*, molar concentration of species *i* in gas phase, *x*, mole fraction of species *i* in gas phase and similarly *y*, mole fraction in gas phase, respectively
k_T; k_{T}'	thermal diffusion ratio (3.1.45); thermal diffusion constant (4.2.64)
k_{gf}, k_{gs}	gas film mass-transfer coefficient on feed side and strip side of a liquid membrane (5.4.97a), (5.4.99a)
$k_{\ell f}$, $k_{\ell s}$; $k_{p\rho}$	liquid film mass-transfer coefficient on feed side and strip side of a liquid membrane (5.4.97b), (5.4.99b); particle mass-transfer coefficient (7.2.217b)

k_{s^+}, k_{s^-}	rate constants for forward and backward interfacial reactions (5.3.40)
$k'_{il}; \dot{k}'_{i1}$	distribution ratio of species i between regions 1 and 2, also called capacity factor (1.4.1); distribution ratio defined by (2.2.19) for species i between streams 1 and 2
k_{cR}, k_{cE}	mass-transfer coefficient in the continuous phase, raffinate based, extract based (6.4.97a,b)
k_{gr}, k_{nu}	rate constant for crystal growth and nucleation, respectively (6.4.51)
$k_{il}; k_{il3}, k_{il4}, k_{ilo}; k_{imo}$	mass-transfer coefficients for species i in liquid phase; value of k_{il} for condition 3, condition 4, channel inlet; species i mass-transfer coefficient through organic filled membrane pore
k_1	first-order reaction rate constant (5.3.7)
k_{1m}	membrane mass-transfer coefficient for species 1 (4.3.1)
K	equilibrium constant for a chemical reaction (3.3.68), or an ion exchange process (3.3.121i), a constant (6.3.49)
$K^x; K^*$	mole fraction based K for a chemical reaction (5.2.35); defined by (5.4.100)
K_1, K_2, K_3	constants in membrane transport (6.3.155a,b)
$K_{Ao}, K_{Aw}; K_{AB}$	overall mass-transfer coefficient of species A based on organic or water phase; equilibrium constant (7.1.42c)
K_c, K_g, K_x, K_y	overall mass-transfer coefficients (3.4.5), (3.4.6)
K_{cE}	K_c based on extract phase (6.4.80)
K_C^A	equilibrium constant for ion exchange reaction (5.2.122)
K_d	equilibrium constant for protein–ion exchange resin binding (4.1.77c), ionization equilibrium constant (5.2.4)
K_{d1}, K_{d2}	dissociation constant for solutes 1 and 2, respectively (5.2.61a), (6.3.29)
$K_i; K_1, K_2, K_3; K_i^a; K_i^\infty$	equilibrium ratio of species i between regions 1 and 2 (1.4.1) or (3.3.61); value of K_i for species 1, 2 and 3; values of K_i in terms of activities (4.1.3); $f_{il}^o \gamma_{il}^\infty / P$ in dilute solution stripping (4.1.19b)
$K_{i\ell}; K_\ell$	overall liquid-phase mass-transfer coefficient for species i (7.1.5a); reaction equilibrium constant in the liquid phase based on molar concentrations (5.2.52a)
$K_{ijc}; k_{ijx}; k'_{ijx}$	molar concentration based overall mass-transfer coefficient for phase j (8.1.1c); j phase mass-transfer coefficient (8.1.60); value of k_{ijx} for equimolar counterdiffusion (8.1.62a)
K_o, K_w	overall mass-transfer coefficient based on organic or aqueous phase, ionization product for water (5.4.41c)
K_{is}, K_{ps}	values of K for ion i/protein (p)–salt (s) exchange on an ion exchange resin (7.1.109d), (3.3.122b)
K_{xE}, K_{xR}	overall mass-transfer coefficient K_x (3.4.5) based on extract phase and raffinate phase, respectively (6.4.77), (6.4.81)
$l; \ell$	length of a device, length of molten zone in zone melting (6.3.109b), characteristic dimension of the separator; constant in (2.2.8a–c), length
ℓ_{ik}, ℓ_{ki}	phenomenological coefficients (3.1.203)
ℓ_{loc}	characteristic length of a local volume corresponding to a point in volume averaging Section 6.2.1.1
ℓ_x, ℓ_y, ℓ_z	dimensions of a rectangular separator, Figure 3.2.1
$L; L_f; L^+$	length of a separator, dimension of length, characteristic crystal size; molar feed flow rate; nondimensional L (7.2.38)
L_{ii}, L_{is}, L_{ss}	phenomenological coefficients for binary system (i, s) (3.1.208), (3.1.209)
L_{ik}, L_{ki}, L_{iT}	phenomenological coefficients (3.1.205)
$L_p; L_p^a; L_p^b$	hydraulic transport parameter in Kedem–Katchalsky model (6.3.158a); value of L_p in perfect region; value of L_p in leaky region
$L_T; L_{\text{min}}; L_{\text{MTZ}}; LUB$	separator length (= L); (7.1.60); Figure 7.1.5(b); (7.1.21g)
$m; m_B; m_i; m_1; m_i^0$	velocity profile constant (7.3.134); moles of B; moles of species i in separator; moles of species 1 in separator; total number of moles of species i in separator
$m_{ij}; m_{ij}^o; m_{ij}(n); m_{ij}^a$	moles of species i in region j, total number of moles of i in region j at $t = 0$; moles of i in region j after nth contact; number of atoms of ith isotope of the element in region j
$m_{i\sigma}$	moles of species i in interfacial region σ

$m_{i,j}$	molality, moles of *i* per kilogram of solvent in region *j*: $j = R$, resin; $j = w$, aqueous phase
$m_{F,R}$	molality of fixed charges in the resin phase
m_p; m_{sl}	mass of particle; solvent moles in stationary liquid phase (7.1.104b)
m_{tj}	total moles of all species in region *j* ($j = f$, feed; $j = 1$, vapor phase; $j = 2$, ℓ, liquid phase)
$m_{11}(\mathrm{t})$, $m_{21}(\mathrm{t})$	moles of species 1 and 2 in region 1 at time *t*
$m_{11}^r(t), m_{21}^r(t)$	values of $m_{11}(t)$ and $m_{21}(t)$ in the case of a chemical reaction
$mo_{\mathrm{p}}^{\mathrm{mag}}$	magnetophoretic mobility (7.3.251)
M; M_i, M_s; M_{sl}	molecular weight, a metal species, number of stages in stripping section of a cascade; value of *M* for species *i*, for solvent *s*; *M* for coating liquid in stationary phase
M_t	average molecular weight of solution (3.1.56)
M_w	magnetization of wire (3.1.23)
M_{se}	seed mass density per unit liquid volume (6.4.40a)
M_T; M_{Ta}, M_{Tb}	suspension density of a crystal-containing solution (2.4.2f), (6.4.18); value of M_T for cases *a* and *b*
$Mo^{(n)}$; $Mo_f^{(i)}$, $Mo_\ell^{(i)}, Mo_v^{(i)}$	*n*th moment of the density function (2.4.1g); *i*th moment of molecular weight density function of feed, liquid and vapor, respectively (6.3.70)
Mo_{fr}^j, Mo_{gr}^j	*j*th moment of crystal size density functions $f(r_p)$ and $f_g(gr)$
MWCO	molecular weight cut off of a membrane
n; n_c	number of species/components in a system, number of contacts, stage/plate number, number of positive charges in a metal ion, number of unit bed elements; number of collectors, number of channels (7.3.109)
$n(r_p)$; n^o; $\tilde{n}(r_p)$	population density function, particle number density function (2.4.2a); nucleation population density parameter (6.4.7); defined by (6.4.46b)
$\boldsymbol{n}_i$; n_{ix}, n_{iy}, n_{iz}; $\boldsymbol{n}_{ij}$	mass flux vector of species *i*, $M_i\boldsymbol{N}_i$; its components in *x*-, *y*- and *z*-directions; $\boldsymbol{n}_i$ through surface area $\mathbf{S}_j$
$\mathbf{n}_k$	outwardly directed unit normal to the *k*-phase surface (6.2.26b–d)

$n_{\max}$; n_{med}, n_{par}	peak capacity (3.2.32) (6.3.26a); refractive index of medium and particle
$\boldsymbol{n}_p$, n_p; n_{py}; n_t	particle number flux, (3.1.65), (3.1.66), (3.1.68); particle flux in *y*-direction; number of turns by gas in a cyclone (7.3.146b)
N; $N(r_p)$; $N(r_{\min}, r_p)$, $\mathrm{N}(r_{p_{\max}})$	total number of stages in a multistage device or in the enriching section of a cascade, anionic species in Donnan dialysis, a metal species, number concentration of molecules; numbers/cm^3, number of particles per unit fluid volume in the size range of $r_{\min}$ to r_p; value of $N(r_{\min}, r_p)$ for $r_{p_{\max}}$
$\tilde{\mathrm{N}}$; N_i	Avogadro's number (6.02×10^{23} molecules/gmol); plate number for *i* (6.3.27a)
N_{A}; N_{A}^r, $N_{\mathrm{A}y}^{\mathrm{t}}$; N_{dil}	molar flux of species A in a fixed reference frame without and with reaction; total molar flux of species A in facilitated transport or counter-transport or co-transport in *y*-direction; normality of diluate solution (8.1.404)
$\boldsymbol{N}_i$; $\boldsymbol{N}_{im}$, $\boldsymbol{N}_{jm}$; N_{ix}, N_{iy}, N_{iz}; N_{ir}; $\boldsymbol{N}_{ij}$; $\lvert N_{iy} \rvert$	species *i* flux; $\boldsymbol{N}_i$ through membrane, $\boldsymbol{N}_j$ through membrane; components of $\boldsymbol{N}_i$ in *x*-, *y*- and *z*-directions; radial component of $\boldsymbol{N}_i$; $\boldsymbol{N}_i$ through surface area $\boldsymbol{S}_j$; magnitude of N_{iy}
N_{iz}^p	*z*-component of species *i* flux, N_{iz}, based on unit pore cross-sectional area (3.1.112a)
N_{oj}; $N_{o\ell P}$; N_p	number of transfer units (8.1.92), (8.1.96); defined in (8.1.96); number of pores per unit area size r_p (6.3.135d)
N_R; N_{S}	flux ratio (3.1.129a); solvent flux
$N_i(r_p)$; N_{it}	number density of crystals having a size less than r_p and growth rate gr_i; total number of crystals per unit volume having a growth rate of gr_i (6.4.41c)
N_t	total number of particles per unit volume (6.4.10)
N_{toE}, N_{toR}	number of transfer units based on extract and raffinate phases, respectively (6.4.86a), (6.4.83)
No_i	number of particles of size r_{pi} (2.4.2k)
NTU	number of transfer units (8.1.54c), (8.1.57c), (8.1.66b), (8.1.67d), (8.1.338)
$\boldsymbol{p}$	dipole moment of a dielectric particle
p	stoichiometric coefficient for product P, kinetic order in the dependence of nucleation rate (6.4.30a)

p_A; p_B; p_i,p_j	partial pressures of species A, species B; species i and species j
p_{Ab}; p_{Ai}; $p_{B,\ell m}$	value of p_A in the gas bulk; value of p_A at gas–liquid interface; logarithmic mean of p_B (3.1.131b)
p_{if}, p_{ij}, p_{ip}, p_{iv}	value of p_i in feed gas, region/stream j, permeate gas, vapor phase
$\overline{p}_{ib}$, $\overline{p}_{ii}$	species i partial pressure in bulk and particle interface, averaged over bed cross section, Figures 3.4.4(a), (b)
pH; pI	indicator of hydrogen ion concentration (5.2.65a); isoelectric point for a protein/amino acid; at $pI = pH$, net charge is zero
pK_i	$-\log_{10} K_{di}$, (5.2.65b) for $i = 1$, (5.2.74b) for $i = 2$, (6.3.29)
P; P^o;P_c	total pressure, system pressure; standard state pressure; critical pressure
$\overline{P}$; P_f; P_j, P_p; P'_p; P_ℓ	local solute permeability coefficient (6.3.157b); feed pressure; total pressure of jth region and permeate, respectively; gas pressure (Figure 7.2.1(b)); gas pressure at the end of a capillary of length l (6.1.5d)
$P_i^0(\pi)$; P_i^*	equilibrium gas-phase pressure for pure i adsorption at spreading pressure π, which is the same for a mixture (3.3.111a); pressure at crossover point for solute i in supercritical extraction
P_{atm}; P_{liq}; P_1, P_2	atmospheric pressure; pressure in the liquid (6.1.12); purification factors (7.2.97)
Pe; Pe_i; Pe_i^m; $Pe_{z,\,eff}$; Pe_{zj}	Péclet number (3.1.143g), (7.3.34d); Pe number for dispersion of solute i (6.3.23a); pore Péclet number (6.3.145a); $(z\, v_z/D_{i,eff,z})$ (7.1.18h); j phase Pe_z (8.1.92)
P_i^{sat}, P_j^{sat}; $P_{iP\ell}^{sat}$; $P_{i,\,curved}^{sat}$	vapor pressure of pure i and pure j, respectively, at system temperature; value of P_i^{sat} on a plane surface; value of P_i^{sat} on a curved surface
P_M^{sat}	value of P_i^{sat} for pure species i of molecular weight M
P_0	amplitude of pressure wave (3.1.48)
P_R, P_w	pressure of resin phase and external aqueous solution, respectively
Po, Pr	power number (6.4.976), power (3.1.47)
q	number of variables in a problem, stoichiometric coefficient for species Q, heat flux in a heat exchanger attached to a cooling crystallizer (6.4.47a), the power of M_T in expression (6.4.39a) for B^0, factor (8.1.150)
q_{fr}	fraction of light reflected (3.1.47)
$q_i(C_{i2})$, $q_{i1}(C_{i2})$, $\overline{q}_{i1}$; q_{i1}^0, q_{i1}^s	moles of species i in solid phase 1 per unit mass of solid phase, cross-sectional average of q_{i1}, initial value of q_{i1}; saturation value of q_{i1}
q_{iR}, q_{is}	moles of species i per unit mass of ion exchange resin (R) or solid adsorbent (s)
q_{maxR}	maximum molar fixed charge density per unit resin mass
$q(\boldsymbol{r}, \boldsymbol{\psi}, \boldsymbol{\lambda})$	probability that a molecule having configuration $(\boldsymbol{r}, \boldsymbol{\psi}, \boldsymbol{\lambda})$ does not intersect pore wall (3.3.89f)
Q	volumetric fluid flow rate, product species in reaction (5.3.5), hydraulic permeability in Darcy's law (6.1.4g,h), heat transfer rate (6.4.47a,d)
Q_c; Q_d	electrical charge of a collector; volume flow rate of dialysate solution
Q_f; Q_g; Q_h; Q_i; Q_ℓ, Q_o, Q_p, Q_R, Q_1, Q_2	volumetric feed flow rate to separator; Darcy permeability for gas through packed bed; amount of heat supplied at a high temperature; electrical charge on 1 gmol of charged species i; amount of heat rejected at a low temperature; volumetric flow rate at membrane channel inlet; electrical charge of a particle; excess particle flux (7.2.123), volumetric flow rate of product stream from separator; heat supplied at the reboiler per mole of feed; volume flow rate of overflow; volumetric rate of underflow/concentrate
Q_{Am}, Q_{Bm}, Q_{im}, Q_{jm}	permeabilities of species A, B, i and j, respectively, through membrane in gas permeation and pervaporation, respectively
Q_{ij}	permeability of species i through region j (= A, B, C, D, 1, 2) of the membrane
Q_{im}^{ov}	overall permeability of species in membrane pervaporation for a membrane of thickness δ_m
Q_{crys}, Q_{sub}	heat transfer rate of a solution during crystallization and subcooling, respectively
Q_{im0}	value of Q_{im} for $C_{im} = 0$
Q_{sm}, Q_{sc}	solvent permeability through membrane and cake in cake filtration
$\mathbf{r}$	vector of molecular position, radius vector, unit vector in radially outward direction

r	radial coordinate, any characterizing property of a continuous mixture
r_1, r_2; r_{1i}, r_{2o}; r_c; r_f	radii of curvature of interface (3.3.47); liquid outlet radii in tubular centrifuge; critical size of a nucleus (3.3.100b), cyclone radius; free surface radius in tubular centrifuge
r_g; r_h; r_i; r_{in}	radius of gyration of a macromolecule; hydrodynamic viscosity based radius (3.3.90f); radius of spherical solute molecule (3.3.90a); radius of liquid–liquid interface in tubular centrifuge
r_o	radius of a sphere whose volume is equal to that of an ellipsoid (3.1.91g), radial location of the center of solute peak profile, radius of a cylindrical centrifuge
r_p; $r_{p,a}$; r_{p1}, r_{p2}; r_{p_i}; r_s; r_t; r_w	radius of particle, pore radius; analytical cut size (2.4.18); particles of two different sizes; dimension of particle of a certain size; particle size for classification (2.4.8); cyclone exit pipe radius; radius of wire
r_{max}, r_{min}; $r_{p,50}$	maximum and minimum radius of membrane pores or particle sizes; equiprobable size
$\sqrt{\overline{r_p^2}}$	hydraulic mean pore radius (3.4.87)
$\bar{r}_p$, $\bar{r}_{p_{1,0}}$, $\bar{r}_{p_{i+1,i}}$	mean of particle size distribution based on $f(r_p)$ and $n(r_p)$, respectively (2.4.1e), (2.4.2g), (2.4.2h)
$\bar{r}_{p_{3,2}}$	Sauter mean radius of a drop, bubble or particle (6.4.89)
ra; re; $re\vert_{\mathrm{flow}}$	rate of arrival of cells; fractional water recovery; value of re in a cell (6.3.172b)
R; R	universal gas constant; radius of a tube or capillary, reflux ratio (2.3.5), (2.3.7), (8.1.137), solute rejection in reverse osmosis, solute retention in ultrafiltration
R_c; $\hat{R}_{c\delta}$, $\hat{R}_{cw}$	cake resistance; specific cake resistance per unit cake thickness and unit cake mass, respectively (6.3.135l)
R_h; R_i; R'_i; R_L	hydraulic radius (6.1.4c); solute rejection/retention by membrane for species i, retention ratio for species i (7.3.211); fraction of solute i in mobile phase (7.1.16c); largest radius of a conical tube
R_m; R_s; R_∞	membrane resistance; resolution between neighboring peaks (2.5.7) in chromatography; value of R_i at large Pe_i^m
R_{A}, R_i	molar rate of production of A per unit volume (5.3.7), (6.2.2d), for species i

R_1, R_2	intrinsic RO rejection of the unionized species 1 and ionized species 2
R^+ (R^-)	ion exchange resin with fixed positive (negative) charge; cation (anion) of a surface active solute
R_{ij};R_{im};$R_{i,\mathrm{reqd}}$	permeation resistance of region j (j = A, B, C, D) in the membrane to species i; membrane permeation resistance of species i; solute i rejection required in a RO membrane
R_{ik}, R_{ki}; R_{min}	phenomenological coefficients (3.1.207); minimum reflux ratio (8.1.170)
R_{obs}, R_{true}; Re; Re_L; Re_{imp}	observed and true solute rejection in ultrafiltration and RO; Reynolds number; Re for a plate of length L (3.1.143a), Table 3.1.5; Re for an impeller (Table 3.1.7), (6.4.96)
s	fractional supersaturation (3.3.98b), power of the ΔP dependence of $\hat{R}_{c\delta}$ (6.3.138j), Laplace transform complex variable (5.4.35), solution volume fed to bed per unit empty bed cross section (7.1.17a), eluent/salt (7.1.109b), salinity (10.1.13)
s_m; s_{mp}, s_{ms}; s_p	pore surface area/membrane volume (6.3.135e); value of s_m for membrane pore volume or membrane solids volume (6.3.135f,g); sedimentation coefficient (4.2.16b)
s_1, s_2	two different solvents
S; S_c	solute transmission/sieving coefficient (6.3.141e), supersaturation ratio (3.3.98c), stripping factor (8.1.135), (8.1.189b); bed/column cross-sectional area
$\boldsymbol{S}_f$, $\boldsymbol{S}_k$, $\boldsymbol{S}_M$; S_j; S_M, S_{d_p}	cross-sectional area vector of feed entrance, kth feed exit and membrane surface area vector in a separator; cross-sectional area of flow for jth stream; selectivities (7.3.219a,b)
S_{ij}; $\overline{S_{ij}}$	molar entropy of species i; partial molar entropy of species i (3.3.17b)
S_{im}; S_{im0}	solubility coefficient of species i in membrane; value of S_{im} for $C_{im} = 0$
S_∞	value of S when $Pe_i^m >> 1$ (6.3.145b)
S_σ; $\overline{S_\sigma}$; S_1, S_2	surface area of interfacial region (Figure 3.3.2A); molar surface area in gas–solid adsorption (3.3.107); sieving coefficients for species 1 and 2
S_{tj}; S_{mag}	total entropy for region j (3.3.3); magnetic field force strength (7.3.251)

S_{obs}; S_{true}	observed solute transmission/sieving coefficient; true value of S
Sc; Sc_c	Schmidt number (3.1.143a); Sc for continuous phase
Sh; Sh_c, Sh_D; Sh_p; Sh_z	Sherwood number (3.1.143a); Sh for continuous phase and dispersed phase, respectively; Sh in a packed bed (7.2.218a); Sh at location z (7.2.64)
St	Stanton number (3.1.143g), Stokes' number (6.3.41)
t; t_{br}; t_c; t_{res}; t_σ	time; breakthrough time; time for cut point in the chromatographic separator output (2.5.1); residence time; thickness of interfacial region (Figure 3.3.2A)
t_i^+; t_1^+, t_2^+; $\bar{t}; \bar{t}_1, \bar{t}_2, \bar{t}_3$	nondimensional time variable for species i (6.3.12); value for t_i^+ for species 1, 2 (3.2.9), (3.2.20); breakthrough time (7.1.15c); value of $\bar{t}$ for species 1, 2 and 3
t_i^{in}, t_i^0	times when species i appears and disappears, respectively, from a chromatographic separator output
t_{im}, t_{is}	transport number of i in membrane or solution (3.1.108d)
t_{s_1}, t_{s_2}	time required for solvents, s_1, s_2 (3.2.24)
$t_{R_i}; t_{R_M}; t_{R_o}$	retention time for species i in capillary electrophoresis (6.3.18a), (7.1.99d); retention time for the mobile phase; retention time based on $v_{z,\text{avg}}$ (7.3.207)
T; T_1; T_2; T_c	absolute temperature; temperature of cooled plate; temperature of the heated plate; critical temperature
T_f; T_g; T_i; T_p	feed temperature; glass transition temperature of a glassy polymer; value of absolute temperature T of region i; product temperature
T_C; T_H, T_L; T_R	temperature of condenser; two temperatures in supercritical extraction; reboiler temperature
T_{cf}; T_{ci}; T_{mi}	temperature of cooling fluid, critical temperature of species i; melting temperature for species i
T_{sat}	temperature at which the solution is saturated
T_{sol}	temperature of the solution due to undergo crystallization
Th	dimensionless group (3.1.46b)
u	number of fundamental dimensions (Section 3.1.4.1)
u_c	mass fraction of solute in the crystallized solution on a solid-free basis

u_i; u_k; u_{ij}; u_{il}; u_{io}; u_{is}; u_{ilb}	mass fraction of impurity species i; mass fraction of species k; mass fraction of species i in region j (1.3.5) or jth stream (2.1.20); value of u_i in melt; value of u_i initially in the solid; value of u_i in the recrystallized solid; value of u_{il} in the bulk melt
u_o; u_{rc}; u_{ro}	mass fraction of solute in the solution charged for crystallization; $u_c/(1-u_c)$; $u_o/(1-u_o)$ (6.4.47b)
u_i^m	ionic mobility (3.1.108j)
u_{iEn}, u_{iRn}	mass fraction of species i in extract and raffinate streams, respectively, from stage n
ur_{ig}, ur_{is}	defined by (8.1.349) and (8.1.350)
ur_{ij}	weight of solute i per unit weight of phase j (9.1.32)
$\boldsymbol{U}_i$; $\boldsymbol{U}_p$	migration velocity vector for species i (3.1.84b); particle velocity vector
$\overline{\boldsymbol{U}}_i$	averaged velocity vector of ith molecules due to all forces
$\overline{\boldsymbol{U}}_i^{\text{new}}$	defined by (3.1.103)
U_{ix}, U_{iy}, U_{iz}	components of migration velocity of species i in x-, y- and z-directions, (3.1.82)
U_{ik}; $\langle U_{ik}\rangle^k$; $\hat{U}_{ik}$	value of $\boldsymbol{U}_i$ in the kth phase/region; average of $\boldsymbol{U}_{ik}$ in the kth phase/region; defined as a fluctuation by (6.2.28)
U_p^{int}; $U_{px^i}^{\text{int}}$; $U_{pr_p}^{\text{int}}$	internal particle velocity vector (6.2.50d); its component in the direction of the internal coordinate x^i; internal particle velocity vector for all particles of size r_p
$\boldsymbol{U}_{pt}$; U_{pr}; U_{prt}; U_{pzt}, U_{pyt}	terminal velocity vector of particle (3.1.62); radial particle velocity; terminal value of U_{pr}; value of $\boldsymbol{U}_{pt}$ in z-direction (6.3.1), (7.2.211), y-direction (7.3.154)
$\boldsymbol{v}, \boldsymbol{v}_t; \boldsymbol{v}^*, \boldsymbol{v}_t^*; \boldsymbol{v}^+, \boldsymbol{v}_t^{ref}; \boldsymbol{v}_{tj}, \boldsymbol{v}_{tj}^*$	mass averaged velocity vector of a fluid (also $\boldsymbol{v}_t$); molar average velocity vector of a fluid (also $\boldsymbol{v}_t^*$); nondimensional $\boldsymbol{v}$ (6.3.39); reference $\boldsymbol{v}_t$; values of $\boldsymbol{v}_t$ and $\boldsymbol{v}_t^*$ on surface area $\boldsymbol{S}_j$ (2.1.1), (2.1.2)
$\boldsymbol{v}_i$; $\boldsymbol{v}_{ij}$	averaged velocity vector of ith species; value of $\boldsymbol{v}_i$ on surface area $\boldsymbol{S}_j$ (2.1.1)
$v_k; v_{kz}; v_k^{\text{int}}$	velocity of region k; z-component of velocity $\boldsymbol{v}_k$ of region k; mass average velocity of the interface of two phases
$\boldsymbol{v}_p^r$	particle diffusion velocity relative to that of the fluid phase (3.1.43)

v_{ci}^*; v_{Ci}^*; v_o; v^{o}; v_{Ci}^{*+}; v_{og}	average velocity of liquid zone carrying species *i* (7.3.208); concentration wave velocity of species *i* (7.1.12a); velocity of micelles, superficial velocity (3.1.176), in a packed bed (6.1.4a); amplitude of square-wave velocity (7.1.72a); nondimensional concentration wave velocity (7.1.105o); superficial velocity for gas phase
v_r; v_s; v_{so}; v_{tw}; v_{tz}; v_{vz}	radial velocity; shell-side velocity (3.1.175), volume flux of solvent/permeate (7.2.71); value of v_s at membrane channel inlet; tangential fluid velocity in wall region (7.3.134); same as v_z; vapor velocity in *z*-direction (6.3.47a)
v_x, v_y; v_{yw}; v_{ywf}	local convective velocity in *x*-direction, *y*-direction; value of v_y at wall; value of v_{yw} at feed entrance (7.2.39)
v_z; $v_{z\max}$; $v_{z,\,\mathrm{avg}}$; $v_{z,\,\mathrm{avg},f}$	velocity of fluid in *z*-direction; maximum value of v_z, averaged value of v_z over flow cross section; value of $v_{z,\mathrm{avg}}$ at feed location (6.1.5f)
v_∞	uniform gas velocity far away from object
v_{fr}; $v_{i,\,\mathrm{eff}}^+$	velocity of freezing interface in zone melting (6.3.110c); nondimensional velocity of species *i* in capillary electrophoresis (6.3.12)
v_z^{AA}; v_{zH}, v_{zL}	velocity of interface AA between suspension and clarified liquid in *z*-direction (4.2.52); interstitial gas velocity at high-pressure feed step and low-pressure purge step, respectively (7.1.53a,b)
v_{EOF}; $v_{\mathrm{EOF},z}$	electroosmotic velocity (6.1.22); value in *z*-direction
vr	defined by (7.2.167)
V; V_b; V_d; V_f; V_h; $\hat{V}_a$; $\dot{V}$; $\overline{V}$	volume of a region, volume of separator, volume of feed solution/eluent passed, volume of a sphere (3.3.52a), voltage between electrodes; volume of buffer; volume of the dialysate solution; volume of feed solution; hydrodynamic volume of a macromolecule/protein (3.3.90f); adsorbed monolayer phase volume/weight of adsorbent (3.3.114b); radial volume flow rate of solution (Figure 7.1.6); defined by (7.1.18i)
$\tilde{V}_c$; V_i; $\overline{V_i}$; V_j	critical molar volume of a species; molar volume of pure species *i*; partial molar volume of species *i*; volume of region *j*: *j* = 1, stationary phase; *j* = 2, mobile phase
V_k; V_l; V_ℓ^p; V_o; V_o^t; V^o	volume of region *k*; liquid volume; specific pore volume of a microporous adsorbent (4.1.64a); volume of organic solvent; total amount of V_o (6.3.99); sample volume (7.1.101b)
V_M; V_p; V_s; $V_{S\ell}$; V_{sp}	mobile-phase volume in a column (7.1.99g); volume of a particle, cumulative permeate volume (7.2.87); stationary adsorbent-phase volume in a column; suspension volume; stationary liquid-phase volume; mobile-phase volume present inside the pores of a particle (7.1.110c)
$\overline{V}_s$; $\overline{V}_t$; V_w; V_σ	partial molar volume of solvent; averaged partial molar volume (3.1.56); volume of water; volume of interfacial region, Figure 3.3.2A
V_{fi}; V_{fe}	initial volume of feed solution; final volume of solution
V_{f0}; V_{fR}; V_{N_i}; V_{R_i}	volume of feed solution at time *t* = 0; volume of retentate; net retention volume for species *i* (7.1.99j), retention volume for species *i* (7.1.99e,f), (7.1.99h)
V_{cap}^{iex}; V_{eff}; V_{channel}	volumetric ion exchange capacity of packed bed; liquid filled centrifuge volume; volume of channel
$\overline{V}_{\mathrm{AY}}$	partial molar volume of electrolyte AY (3.3.119b)
$\overline{V}_{ic}$	value of $\overline{V}_i$ for a crystal of *i*
V_{im}	molar volume of species *i* at its normal boiling point
$\overline{V}_{ij}$	value of $\overline{V}_i$ in region *j*
VCR	volume concentration ratio (V_{f0}/V_{fR}) (6.4.98)
w; w_{crys}; w_i; w_{so}	mass of adsorbent, quantity defined by (5.2.54); mass of crystals formed at any time, mass of solute *i* charged; mass of solution charged to the crystallizer
w_{ij}; w_{tj}; w_{tz}; w_{tj}^s; w_{tE}, w_{ER}	mass flow rate of species *i* through $\boldsymbol{S}_j$ (2.1.4); total mass flow rate through $\boldsymbol{S}_j$ (2.1.5); total mass flow rate in *z*-direction; total solids flow rate in *j*th stream (2.4.3a); w_{tj} for *j* = extract, *E*, w_{tj} for *j* = raffinate, *R*
w_E, w_M, w_R	weight of mixture at *E*, *M* and *R*, respectively
w^l; w^s; $w_p^s(r_p)$; wa	mass of stationary liquid phase used as coating; mass of particles per unit of fluid volume (2.4.2e); mass of a solid particle of size r_p (2.4.2e); waist size of a light beam

W, W_{A}	width of rectangular channel walls, molar transfer rate of species A
$\underline{W}$	total reversible work done (3.1.25a,b)
W_{bi}, W_{ij}, W_{tj}	band width of the chromatographic output of species i (Figure 2.5.2), molar flow rate of species i through $\boldsymbol{S}_j$ (2.1.7), total molar flow rate through $\boldsymbol{S}_j$ (2.1.8)
$W_{t\mathrm{A}m}$, $W_{t\mathrm{B}m}$	molar rate of permeation of species A and B through membrane
W_{tf}, W_{tl}, W_{tv}	molar flow rate of feed, liquid fraction and vapor fraction, respectively
W_{tlb}, W_{tld}	total molar flow rate of bottoms product and distillate product from a distillation column
W_{t1}, W_{t2}, W_{tp}	total molar flow rate of streams $j = 1$, $j = 2$ and j = permeate
W_{tjn}^{t}	total molar flow rate of stream j for stage n in enriching section of cascade
We	Weber number, $(\rho_c\, v_c^2\, d_p/\gamma)$ (6.4.91)
x, x_{A}	coordinate direction, mole fraction of species A in liquid phase
x_{A}^{*}	hypothetical liquid phase mole fraction of species A in equilibrium with $y_{\mathrm{A}b}$
$x_{\mathrm{A}b}$, $x_{\mathrm{A}i}$	bulk liquid mole fraction of species A, value of x_{A} at a two-phase interface
x_i, x_{ij}, $x_{i\sigma}$, $x_{i,j}$	mole fraction of species i, value of x_i (i = A,B, 1, 2, s(solvent), etc.) in region j or stream j (j =1, 2, f(feed), g = gas, l = liquid, p = permeate, R = resin, s = solution, v = vapor, w = water), x_{ij} where j=σ, the surface adsorbed phase, mole fraction of species i in region j when molecular formula is substituted for species i
x_{iE}, x_{iE}^{*}, x_{iE}^{e}	mole fraction of species i in extract phase, value of x_{iE} in equilibrium with x_{iR}, value of x_{iE} if both streams leave stage in equilibrium
x_{ilb}, x_{ild}	bulk value of x_{il}, mole fraction of i in liquid product from reboiler in a distillation column, x_{il} in liquid product from condenser at the top of a distillation column
x_{iR}, x_{iR}^{*}, x_{iR}^{e}	mole fraction of species i in raffinate phase, value of x_{iR} in equilibrium with x_{iE}, value of x_{iR} if both streams leave stage in equilibrium
x_{jf}, x_{jp}, $x_{ip}^{'}$	mole fraction of species j in feed and permeate, respectively, mole fraction (Figure 7.2.1(b))

$x_{s,lm}$	defined by (3.1.137)
X	molar density of fixed charges in electrically charged system
X_{ij}, X_{ijn}	mole ratio of species i in region j (1.3.2) or stream j (2.2.2d), X_{ij} for state n
X_{ij}^{a}	abundance ratio of isotope i in region j (1.3.7)
y, y_f	coordinate direction, normal to gas–liquid, liquid–liquid or membrane–fluid interface, feed gas mole fraction (Figure 7.1.14)
y_i, y_{A}, y_H, y_L	mole fraction of species i and A in vapor/gas phase, respectively, fluid mole fraction (7.1.62b), gas-phase mole fractions defined by (7.1.54a)
y_{A}^{*}, $y^{*'}$, $y_{\ell im}$	hypothetical gas-phase mole fraction of species A in equilibrium with $x_{\mathrm{A}b}$, nondimensional y-coordinate (5.3.5j), y-coordinate of limiting trajectory (7.3.263a)
$y_{\mathrm{A}b}$, $y_{\mathrm{A}i}$	bulk gas mole fraction of species A, value of y_{A} at a two-phase interface
Y_{ij}, Y_{iR}, Y_2, $Y_{2,f}$	segregation fraction of species i in region j (1.3.8a), segregation fraction of solute i in retentate in a membrane process (6.4.107), defined by (7.2.19) and (7.2.20)
$Y_{11}(t)$, $Y_{21}(t)$	segregation fraction of species 1 and 2 in region 1 at time t
Y_{ij}^{a}, $\dot{Y}_{ij,}$ $\dot{Y}_{rj}$	segregation fraction for an isotopic mixture (1.3.9a), of species i stream j (2.2.12), of particles of size r in stream j (2.4.5)
z, z_{cr} (or z_{crit}), z_H, z_L, z_{AA}, z_{BB}	coordinate direction, critical distance (7.2.133), characteristic locations at pressures P_H and P_L (7.1.55e), vertical coordinates of interfaces AA and BB, respectively
z_{HL}, z_{HS}	height of the liquid level of a dilute suspension, height of sludge layer
z^{+}, z_i^{+}	nondimensional z-coordinate (Figure 3.2.2), (6.3.12), value of z^{+} for center of mass of concentration profile of species i (3.2.22a,b)
z_{α}, z_{β}, $z_o(\overline{C}_{i2})$	z-coordinate locations of regions α and β, respectively, defined by (7.1.17e,f)
Z_i, $Z_{i,\mathrm{eff}}$, Z_p	electrochemical valence of species i, effective charge on ion i due to the diffuse double layer ($< Z_i$) (6.3.31a), value of Z_i for a protein

Greek letters

α	constant in (3.1.215), separation factor between two species 1 and 2 in capillary electrophoresis (6.3.27e)
$\alpha_f, \alpha_l, \alpha_v$	parameters for feed, liquid fraction, vapor fraction in a continuous chemical mixture described by a Γ distribution function (4.1.33f), (6.3.71)
$\alpha_{ij}; \alpha_{ij}^{hf}, \alpha_{ij}^{ft}, \alpha_{ij}^{ht}; \alpha_{ijn}$	separation factor between two species i (i = 1, A, s (solvent)) and regions j (j = 2, B (species), i), value of α_{ij} between two streams (2.2.3), (2.2.4), (2.2.2a); value of α_{ij} for nth plate
α_{in}	multicomponent separation factor between species i and n (1.6.6)
$\alpha^{'}$	separation factor of Sandell (1.4.15)
$\alpha_{\mathrm{AB}}^{*}; \alpha_{ij}^{\mathrm{evap}}; \alpha_{ij}^{\mathrm{perm}*}$	value of α_{AB} under ideal condition of zero pressure ratio (6.3.198), (8.1.426); value of α_{ij} for evaporation only (6.3.180); ideal separation factor in vapor permeation (6.3.180)
β	defined by (2.2.8a,b), exponent in (3.3.89a), indicator of macromolecular shape for a given r_g (3.3.90e), constant in (3.1.215), defined by (7.1.52b), (7.2.58), (7.2.138)
$\beta_f, \beta_\ell, \beta_v$	compressibility of fluid (3.1.48), parameters for feed, liquid fraction and vapor fraction in a continuous chemical mixture (4.1.33f), (6.3.71)
$\beta_i; \beta_p; \beta_{\mathrm{A}}, \beta_{\mathrm{B}}; \overline{\beta}; \overline{\beta}_c$	exponent in (3.3.112c), parameter (7.2.18); compressibility of particle (3.1.48); defined by (7.1.52a); coefficient of volume expansion (6.1.9); a parameter (6.4.129); coefficient of thermal expansion of solution density (7.3.233)
$\gamma; \gamma_{cr}; \gamma_{\mathrm{A}}; \gamma_R; \gamma_{R_2}$	surface tension, interfacial tension, pressure ratio (6.3.197), (6.4.123), (8.1.426), parameter (7.1.18f); critical surface tension for a polymer; Damkohler number ($k_b\delta_m^2/D_{\mathrm{A}}$) (5.4.100); ($D_{\mathrm{A}}k_1/k_\ell^2$) (5.3.11); defined by (5.3.35j)
$\gamma_f, \gamma_\ell, \gamma_v$	parameters for feed, liquid and vapor fraction (4.1.33f), (6.3.69)
$\gamma_i; \gamma_{if}, \gamma_{ij}; \gamma_{jf}$	activity coefficient for species i, dimensionless steric correction factor; value of γ_i in feed stream, in phase j; value of γ_j in feed stream (species j)
$\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma^{12}; \gamma^{SL}, \gamma^{LG}, \gamma^{SG}$	factors/parameters in plate height (7.1.107f–i); interfacial tension between two bulk phases 1 and 2; interfacial tension between phases S and L, L and G, S and G, respectively (S = solid, L = liquid, G = gaseous)
$\dot{\gamma}; \dot{\gamma}_w$	shear rate (3.1.74), (6.1.31); wall shear rate
$\gamma_{il}^{\infty}; \gamma_{il,u}^{\infty}$	infinite dilution activity coefficient for species i in the liquid; activity coefficient of species i in liquid phase on a mass fraction basis at infinite dilution (6.3.83)
$\mathit{\Gamma}_{is}^{E}$	molar excess surface concentration of species i/cm^2 of pore surface area (3.1.117a)
$\mathit{\Gamma}_{i\sigma}; \mathit{\Gamma}_{i\sigma}^{E}$	surface concentration of species i (3.3.34); algebraic surface excess of species i (3.3.40b), (5.2.145a)
$\delta; \delta(x), \delta(z), \delta(z^+); \delta_c$	falling film thickness; delta function in x-, z- and z^+-directions (3.2.14b); cake layer thickness
$\delta_g; \delta_i; \delta_\ell; \delta_m; \delta_s; \delta^{'}{}_\ell$	thickness of gas film; solubility parameter of species i, characteristic thickness of concentration profile (7.3.202); thickness of liquid film; membrane thickness, pore length; sorbed surface phase thickness (3.1.118b); thickness of liquid film from phase interface to reaction interface (5.3.22)
$\delta_{\mathrm{A}}, \delta_{\mathrm{B}}, \delta_{\mathrm{C}}$	membrane thickness in regions A, B, C of a membrane (Figure 6.3.35(b))
$\delta_1, \delta_2, \delta_n$	thickness of layer 1, layer 2, layer n in a composite membrane
$\Delta C; \Delta E_s; \Delta G; \Delta G_t; \Delta H_s; \Delta P; \Delta S; \Delta T$	molar supersaturation (3.3.98a); activation energy for crystal growth rate (3.4.29); Gibbs free energy change, e.g. for forming a crystal (3.3.100a); change in Gibbs free energy for all molecules; enthalpy of solution of a gas species in a polymer; pressure difference ($P_f - P_p$), etc.; selectivity index (7.2.93); extent of supercooling (3.3.98d), temperature difference ($T_2 - T_1$)
ΔH_{crys}	heat of crystallization
$\Delta \mathrm{G}^0, \Delta \mathrm{H}^0, \Delta \mathrm{S}^0$	standard Gibbs free energy change, enthalpy change and entropy change for a reaction
$\Delta d_p; \Delta r_p; \Delta w^s$	particle diameter difference between two consecutive sieves; ($\Delta d_p/2$) or the net growth in size of all seed crystals (6.4.40i); mass of crystals retained on a sieve of given size

$\Delta x, \Delta y, \Delta z,$ $\Delta z_L, \Delta z_H$	lengths of a small rectangular volume element in three coordinate directions, defined by (7.1.53a,b)
$\Delta\mu_i^0; \Delta v_1, \Delta v_+,$ $\Delta v_-, \Delta\pi$	$\mu_{i1}^0 - \mu_{i2}^0$, number of water molecules, cations and anions, respectively released during binding; osmotic pressure difference $(\pi_f - \pi_p)$
$\Delta\rho_i$; $\Delta\rho_{i,\text{sat}}$; $\Delta\phi$	mass concentration change of species i in crystallizer (6.4.24); change in saturation concentration due to ΔT (6.4.51); potential difference between two phases
Δ_R	defined by (8.1.328)
∇^i	del operator in internal coordinates x^i, y^i and z^i
ε	void volume fraction in a packed bed, electrical permittivity of the fluid $(= \varepsilon_0\varepsilon_d)$
ε_a; ε_b	phase angle; fractional cross-sectional area of membrane which is defective
ε_d; ε_i; ε_k	dielectric constant of a fluid, porosity of particle deposit on filter media; Lennard–Jones force constant for species i; volume fraction of phase k in a multiphase system
$\varepsilon_m;\varepsilon_p;\varepsilon_0;\varepsilon_0$	porosity of membrane, pellet, bead or particle; dielectrical constant of a particle; electrical permittivity of vacuum; porosity of spacer in spiral-wound module (3.1.170), porosity of clean filter
ε_B; ε_C	fractional area of defects in glassy skin region B (Figure 6.3.35(b)); value of fractional membrane cross section in region C
ε_{12}	enrichment factor for species 1 and 2 (1.4.10), (2.2.2e)
ζ	zeta (electrokinetic) potential (3.1.11a)
η	recycle ratio (2.2.22), nondimensional variable (3.2.11), (6.3.14b), (6.3.114), fraction of particles collected (7.3.37), (7.3.38), (7.3.46), intrinsic viscosity
η^+	variable defined by (3.2.17)
η_i; η_j; η_{ij}; η_j', $[\eta]; [\eta]_i; \eta_{iF}$	variable (2.5.5), η for species i (3.2.25); impurity ratio for region j (1.4.3a); impurity ratio for ith species in region j (1.6.4); defined by (1.4.4); intrinsic viscosity (3.3.90f); its value for polymer i (7.1.110f); current utilization factor (8.1.406)
$\langle\eta_i\rangle;\langle\eta_i^2\rangle$	first moment of $C_i(\eta_i, t_i^+)$ (3.2.26); defined by (3.2.29)

θ	cut (2.2.10a), stage cut, fraction of adsorbent sites occupied (3.3.112a), contact angle, gas–liquid–solid system (Figure 3.3.16), contact angle between membrane surface and liquid (6.3.140)
θ_i	component cut for species i (2.2.10b), Langmuir isotherm (7.1.36a), nondimensional mobile phase concentration (7.1.18b)
θ_{id}, θ_{kd}	component cut for species i and k, respectively, in the distillation column top product (8.1.224)
$\kappa_{\mathrm{A}o}$; κ_d;κ_i	distribution coefficient of species A between aqueous and organic phases (3.4.16); reciprocal Debye length (3.1.17); distribution coefficient of species i
$\kappa_{i1}, \kappa_{i1}^N$	distribution coefficient of species i between regions 1 and 2 (1.4.1), its Nernst limit (3.3.78), (3.3.79)
$\kappa_{if}; \kappa_{ij}; \kappa_{im}$	partition coefficient of solute i between feed solution and feed side of the membrane; partition/distribution coefficient of solute i between two immiscible phases; κ_{ij} for feed solution and the membrane (3.3.87), (3.3.89a)
$\kappa_{ij}', \kappa_{ij}''$	effective value of κ_{ij} when there is no reaction or there is reaction
κ_{io}	partition coefficient of i between an organic and an aqueous phase (6.3.101a)
κ_{ip}	κ_{im} at permeate–membrane interface (3.4.58)
$\kappa_{i,\,\mathrm{loc}}(\boldsymbol{r})$	local equilibrium partition constant (3.3.89g)
$\kappa_{is}, \kappa_{is}'$	impurity distribution coefficient (6.3.109a)
$\kappa_{is,\,\mathrm{eff}}'$	effective partition coefficient in zone melting for species i (6.3.119a)
κ_{iE}	distribution (partition) coefficient for species i in solvent extraction
κ_{iR}	distribution coefficient of i in ion exchange system (3.3.115)
κ_{p_1}; κ_{p1}^0	protein partition coefficient in aqueous two-phase extraction; protein distribution coefficient in the absence of a charge gradient at interface
κ_salt^m	distribution coefficient of salt, molal basis (4.1.34o)

λ	Debye length (3.1.10b), mean free path of a gas molecule (3.1.114), filter coefficient (7.2.187), parameter for a dialyzer (8.1.399), parameter for a distillation plate/stage (8.3.38), latent heat of vaporization/condensation
$\boldsymbol{\lambda}$; λ_x, λ_z; λ_i; λ_+; λ_-; λ_i^o	molecular conformation coordinate (3.3.89c); electrode spacings (7.3.18); retention parameter for species i (7.3.213), ionic equivalent conductance of ion i (3.1.108r); value of λ_i for a cation; value of λ_i for an anion; value of λ_i at infinite dilution (Table 3.A.8)
λ_1, λ_2	defined by (5.4.100)
Λ	equivalent conductance of a salt (an electrolyte) (3.1.108s)
μ; μ_0; μ_{dr}	dynamic fluid viscosity; value of μ at inlet; viscosity of drop fluid
μ_C, μ_D	fluid viscosity of continuous and dispersed phases, respectively
μ_{EOF}^m	electroosmotic mobility (6.3.10c)
μ_i, μ_i^0, μ_i^m; $\mu_{i,\mathrm{eff}}^m$; $\mu_{\mathrm{ion},g}^m$	species i chemical potential and its standard state value; ionic mobility of ion i (3.1.108m); effective value of μ_i^m (6.3.8d,g); ionic mobility of ion in gas phase
μ_{ij}; μ_{ijn}; $\mu_{ij}^{\mathrm{e}\ell}$	value of μ_i in region j; value of μ_{ij} for plate/stage n; value of μ_{ij} in a system with electrical charge (3.3.27)
$\mu_{ij\mathrm{Pl}}$	value of μ_{ij} for a planar interface (3.3.50)
$\mu_\ell(M), \mu_v(M)$	chemical potential of species of molecular weight M in liquid and vapor phases, respectively, in continuous chemical mixtures
$\mu_0^m, \mu_p^m, \mu_s^m$; μ_∞	magnetic permeabilities of vacuum, particle and solution, respectively; chemical potential of a crystal
ν; $\nu(z)$; ν_0	kinematic viscosity; ν at axial location z; ν at inlet
ν_i	stoichiometric coefficient for species i in any chemical reaction
$\nu_{\mathrm{A}}, \nu_{\mathrm{Y}}$	moles of ions A and Y produced by dissociation of 1 mole of electrolyte AY
ξ	extent of separation for a binary system (1.4.16), (2.2.11), (6.3.105)
$\xi_{12}, \xi_{r_{p_1}, r_{p_2}}$	extent of separation for components 1 and 2 in particle classification (2.4.9), for particles of size r_{p_1} and r_{p_2} (2.4.6)

π; π	constant (3.1416…); osmotic pressure, spreading pressure (3.3.41a)
π_f; π_i; π_p, π_w	osmotic pressure of feed solution; spreading pressure in adsorption of solute i from a solution (4.1.63a); osmotic pressures of permeate solution and the solution at the membrane wall, respectively
π_1, π_2	osmotic pressure of solution in regions 1 and 2
ρ; ρ_b; ρ_c; ρ_e; ρ_f; ρ_{fm}; ρ_i; ρ_{ij}	fluid density; bulk density of the packed bed; density of continuous phase (also fluid density at critical point); electric charge density per unit volume; density of feed fluid; moles/fluid volume; mass concentration of species i (also density of solute i (3.3.90b)); value of ρ_i in region j (1.3.4)
ρ_ℓ; ρ_p; ρ_{pg}; ρ_s; ρ_t; ρ_{tj}	density of liquid (melt); mass density of particle material; particle mass concentration in gas; density of solid material; total density of fluid; total mass density of mixture in region j (1.3.5)
ρ_v; ρ_{i1}, ρ_{if}	density of vapor phase; mass concentration of species i in crystallizer outlet solution and feed solution, respectively
$\rho_{i\ell}$; ρ_{ip}; ρ_{p,r_p}	mass density of species i in liquid (melt); mass density of crystals of species i; mass density contribution of particles of size r_p to $r_p + dr_p$ (6.2.55)
ρ_R; ρ_1, ρ_2	density of resin particle, reduced density of fluid ($= \rho/\rho_c$); density of liquids 1 and 2
ρ_{dR}; ρ_{pR}	fluid resistivity; particle resistivity
ρ_{avg}; $\rho_{i\mathrm{sat}}$	average gas density (6.1.5e); mass density of solute i in solution at saturation
$\overline{\rho}_{ik}, \overline{\overline{\rho}}_{ik}$	intrinsic phase average and phase average, respectively, of ρ_{ik} (6.2.24a,b)
$\rho_{ik,\mathrm{avg}i}$	$\overline{\rho}_{ik}$ (6.2.24a)
$\langle\rho_i\rangle$	mass density of solute i in solution averaged over flow cross section (6.2.16b)
σ	electrical conductivity of the solution (3.1.108q), particle sticking probability
σ_i	standard deviation of any profile (3.2.21a,b), Lennard–Jones parameter, ionic equivalent conductance (3.1.108r), solute i reflection coefficient through membrane (6.3.157a,b)

$\sigma_p; \sigma_v, \sigma_v^i; \sigma_x, \sigma_y$	steric factor for protein SMA model (3.3.122d); specific volume based deposit in filter (7.2.172), (7.2.189); standard deviations (7.3.173)
$\sigma_{\mathrm{AB}}; \sigma_{ix}$	average of σ_{A} and σ_{B} (3.1.91b); standard deviations (7.3.12a)
$\sigma_i^+; \overline{\sigma}_m$	nondimensional standard deviation of a profile (3.2.21a,b); average electrical conductivity of the ionic and electronic species in a mixed conducting membrane
$\sigma_{ti}, \sigma_{zi}; \sigma_{zi}^+; \sigma_{Vi}$	standard deviation in the output profile of species i in t-coordinate and z-coordinate, respectively (2.5.3), (6.3.18c,b); nondimensionalized σ_{zi} (6.3.16b); standard deviation in volume flow units (7.1.102b)
$\tau; \tau_m; \tau_w; \tau_{wc}$	tortuosity factor; value of τ for porous membrane; wall shear stress (7.2.118); τ_w in cake region (7.2.136a)
τ_{yx}, τ_{yz}	components of tangential stress τ_y in x- and z-directions (6.1.24)
$\phi; \phi_{\mathrm{A}}, \phi_{\mathrm{B}}$	potential of any external force field (also ϕ^{ext}), angle in spherical polar coordinate system, enhancement factor due to reaction, solids volume fraction profile in suspension boundary layer (7.2.109); enhancement factors for species A and B
$\phi_c; \phi_D, \phi_s$	volume fraction of solids in cake; volume fraction of continuous, dispersed phase (Table 3.1.7), (6.4.88); volume fraction of particles and solids in a suspension
$\phi_j; \phi_m$	electrical potential of phase j; defined in (7.1.107h)
$\phi_{i\ell}; \phi_{im}; \phi_m;$ $\phi_p; \phi_{p\ell}$	volume fraction of species i in liquid phase; volume fraction of species i in membrane; polymer volume fraction in membrane; voltage drop over a cell pair in electrodialysis; volume fraction of polymer in liquid phase
ϕ_N	correction factor for nonequimolar counterdiffusion (3.1.136b)
ϕ_0	arbitrary value of centrifugal potential at $r = 0$ (3.1.6d)
ϕ_w	volume fraction of water in resin, particle volume fraction at wall
$\phi_{\max}$	maximum enhancement due to an instantaneous reaction, maximum particle volume fraction

$\phi_i^{\mathrm{ext}}; \phi_{i\alpha}^{\mathrm{ext}}, \phi_{i\beta}^{\mathrm{ext}}$	value of ϕ or ϕ^{ext} for any species i; values of ϕ_i^{ext} in regions α and β
$\Phi; \hat{\Phi}_{ig}; \Phi_i^{\mathrm{sat}}$	fugacity coefficient (3.3.56); fugacity coefficient of species i in a mixture in gas phase; value of $\hat{\Phi}_{ig}$ for pure i at P_i^{sat} at system temperature
$\phi_i^{\mathrm{tot}}; \phi_i^*; (\phi_i^*)_{\max};$ $\phi_i^+; (\phi_i^+)$	defined by (3.2.4); defined by (3.2.5b), defined by (3.2.6); defined by (3.2.9) and (6.3.14a)
ϕ_{ti}^{ext}	$\sum \phi_i^{\mathrm{ext}}$, summation over different external forces (3.2.4)
χ, χ_p, χ_s	volume suspectibility of fluid, particle and the solution
χ_{ij}, χ_{ip}	Flory interaction parameter between species i and j and species i and polymer
$\boldsymbol{\psi}; \psi$	molecular orientation coordinate vector (3.3.89c); extent of facilitation of flux (5.4.58) (5.4.59a), selectivity (7.2.92)
ψ_k	any property or characteristic of the kth phase
ψ_s, ψ_v	shape factor for particle surface and volume (Example 2.4.1), (2.4.2e) (3.4.26), (6.4.15), (6.4.19)
ψ_{As}	association factor (3.1.91a)
$\psi_{e\ell}$	electrical potential in the double layer
$\langle \psi_k \rangle$	phase average of ψ in the kth phase (6.2.25a) = $\psi_{k,\mathrm{avg}}$
$\langle \psi_k \rangle^k$	intrinsic phase average of ψ in the kth phase (6.2.25b) = $\psi_{k,\mathrm{avg}i}$
ω	angular velocity, solute permeation parameter (6.3.158b), sign of fixed charge in (3.3.30b)
$\Omega_{D,\mathrm{AB}}$	quantity in diffusion coefficient expression (3.1.91b)

Superscripts

a; b; Br	activity based; bottom/stripping section of a column; Brownian motion
d, drag	drag
eff; eph; ext	effective; electrophoretic; external
ft; G	between the feed stream and the tails stream; gas phase
hf	between the heads stream and the feed stream
ht	between the heads stream and the tails stream
i; iner; int	species i; inertial; internal

L	liquid phase
m	magnetic, mobility, based on molal quantities, maximum number
N	related to Nernst–Plank equation (3.1.106)
0, o	location $z = 0$, standard state, infinite dilution, original quantity
oo, ov	(7.1.101c), overall
p	pore, pure species
P	mole fraction based in Henry's law
r	quantity in a system with recycle or reflux, for the case of a chemical reaction
s	related to solids only in solid–fluid separation, at saturation, scrubbing cascade
S	solid phase
t, T	total value, top/enriching section of a column, thermal diffusion
$v\ell$	vapor liquid
x, δ	mole fraction based, location $z = \delta$ or δ_m
∞	infinite dilution condition
$'$	equimolar counterdiffusion case, first derivative, feed side of membrane
$''$	permeate side of membrane
$+$	nondimensional quantity
$*$	hypothetical quantity

Subscripts

atm; b	atmospheric; bulk phase value, bottom product stream from a column, backward reaction
A,B,C	species A, B and C
c	based on molar concentration, continuous phase, cake, critical quantity
d	diffusive, dialysate phase, dissociation, distillate
D	drag related, Henry's law species related, dispersed phase
e	enriching section
eff; ex; ext	effective value; exit location; external
f; fr	feed side, feed based; during formation of drop, size based
g; gr	gas phase; growth based
H; hex	high; heat exchanger
i	species i, where i = 1, 2, 3, A, B, M, s, phase interface, ith module/tube/stage
ij	ith species in jth stream, $j = f$ for a single feed stream, $j = f_1, f_2$ for two feed streams entering separator, j = 1,2 for product streams rich in species 1 and species 2, respectively
imp; iner	impeller; inertial
in; ion	at inlet; ionic species
j	region/phase j, where j = 1, 2, E, f, g, l, $\ell' m$, o, p, R, s, t, v, w, T, σ
k	species k
l, liq; loc; ℓ'; ℓ; L	liquid phase; local; adhering liquid phase on crystal; low; at end of separator of length L
m; mc; max; min	membrane phase; micellar; maximum; minimum
M	mixture, molecular weight based, metallic species
ME, MR	Murphree based on extract phase, raffinate phase
n, $(n+1)$, $(n-1)$	stage number n, $(n+1)$ and $(n-1)$, respectively
N; nu	metallic species; nucleation
o; obs; og; ol; out	organic phase; observed; overall gas phase based; overall liquid phase based; at outlet
p; pd; P	permeate side, product side, particle; dominant particle; planar interface
r; r_{p_1}, r_{p_2}; R	radial direction; related to particles of size r_1 or r_2; ion exchange resin phase, resistive, raffinate phase
s	solvent, surface integration step in crystallization, surface adsorption site, salt/eluent counterion, stripping section, stage number
s^+, s^-; se	forward and reverse surface reaction; seed crystal
S	location S, stationary phase
t; tOE; tOR	total, top product stream in a column; transfer units (overall) based on extract phase; transfer units (overall) based on raffinate phase
tj	total quantity in jth stream, $j = f$ for a single feed stream, $j = f_1, f_2$ for two feed streams entering separator, j = 1,2 for product streams rich in species 1 and 2, respectively
true; T	true value; thermal diffusive, total
v;w	vapor phase, volumetric; aqueous phase, water
x	liquid mole fraction based, coordinate direction
y	gas phase mole fraction based, coordinate direction
Y	as in species AY
z	coordinate direction
1, 2	species 1 and species 2, phase 1 and phase 2
3, 4	species 3 and species 4, phases 3 and 4
α, β	phase α and phase β
σ, s	surface phase

Abbreviations and acronyms

Å	angstrom
AEM	anion exchange membrane
atm	atmosphere
avg	average
AVLIS	atomic vapor laser isotope separation
BET	Brunauer–Emmett–Teller
bar	10^5 pascal
barrer	unit for permeability coefficient of gases through membrane, $1\text{barrer} = 10^{-10}\dfrac{\text{cm}^3(\text{STP})\text{-cm}}{\text{cm}^2\text{-s-cmHg}}$
Btu	British thermal unit
CAC	continuous annular chromatograph
CACE	counteracting chromatographic electrophoresis
CCEP	countercurrent electrophoresis
CD(s)	cyclodextrin(s)
CDI	capacitive deionization
CE	capillary electrophoresis
CEC	capillary electrochromatography
CEDI	continuous electrodeionization
CEM	cation exchange membrane
CFD	computational fluid dynamics
CFE	continuous free-flow electrophoresis
CGC	countercurrent gas centrifuge
CHO	Chinese hamster ovary
CHOPs	Chinese hamster ovary cell proteins
cm Hg	pressure indicated in the height of a column of mercury
CMC	critical micelle concentration
CMS	carbon molecular sieve
CSC	continuous-surface chromatography
CSTR	continuous stirred tank reactor
CSTS	continuous stirred tank separator
CV	control volume
CZE	capillary zone electrophoresis
ED	electrodialysis
ELM	emulsion liquid membrane
EOF	electroosmotic flow
ESA	energy-separating agent
FACS	fluorescence-activated cell sorting
FFE	free-flow electrophoresis
FFF	field-flow fractionation
FFM	free-flow magnetophoresis
GAC	granular activated carbon
GLC	gas–liquid chromatography
GPC	gel permeation chromatography
HDPs	high-density particles
HETP	height of an equivalent theoretical plate
HFCLM	hollow fiber contained liquid membrane
HGH	human growth hormone
HGMS	high-gradient magnetic separation
HK	heavy key
HPCE	high-performance capillary electrophoresis
HPLC	high-performance liquid chromatography
HPTFF	high-performance tangential-flow filtration
IEF	isoelectric focusing
ILM	immobilized liquid membrane
IMAC	immobilized metal affinity chromatography
ITM	ion transport membrane
ITP	isotachophoresis
LDF	linear driving force approximation
LK	light key
LLC	liquid–liquid chromatography
LM	logarithmic mean
LRV	log reduction value
LSC	liquid–solid adsorption chromatography
LTU	length of transfer unit
mAB	monoclonal antibody
MBE	moving boundary electrophoresis
ME	multiple effect
MEKC	micellar electrokinetic chromatography
MEUF	micellar enhanced ultrafiltration
MSA	mass-separating agent
MSC	molecular sieve carbon
MSF	multistage flash
MSMPR	mixed suspension, mixed product removal
MTZ	mass-transfer zone
NEA	nitrogen-enriched air
OEA	oxygen-enriched air
PAC	powdered activated carbon
PBE	population balance equation
PSA	pressure-swing adsorption
psia	pound force per square inch absolute
psig	pound force per square inch gauge
RO	reverse osmosis
SCF	supercritical fluid
SEC	size exclusion chromatography
SLM	supported liquid membrane
SMA	steric mass action
SMB	simulated moving bed
SPs	structured packings
TDS	total dissolved solids
TFF	tangential-flow filtration
TOC	total organic carbon