

HETEROGENEOUS REACTIONS: Analysis, Examples, and Reactor Design

Volume 1: Gas–Solid and Solid–Solid Reactions

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Preface

The first major book on the design of certain classes of chemical reactors appeared in the late 1940s as Volume 3 of the now classical *Chemical Process Principles* by O. A. Hougen and K. M. Watson. This was followed by several books in the 1950s and 1960s: J. M. Smith's *Chemical Engineering Kinetics*, Octave Levenspiel's *Chemical Reaction Engineering*, G. Astarita's *Mass Transfer with Chemical Reaction*, P. V. Danckwerts's *Gas-Liquid Reactions*, H. Kramer's and K. R. Westerterp's *Elements of Chemical Reactor Design and Operation*, and K. Denbigh and J. C. R. Turner's *Chemical Reactor Theory*. Each book had as its main theme one or two classes of reactions, such as gas-solid (catalytic), gas-liquid, or homogeneous. The 1970s saw a series of books, again on practically the same systems, but with greater emphasis on analysis and mathematical modeling. Among these may be mentioned the books by J. J. Carberry; J. Szekely, J. W. Evans, and H. Y. Sohn; G. F. Froment and K. B. Bischoff; J. B. Butt; and Y. T. Shah. With the exception of *Chemical Reactor Analysis and Design* (by G. F. Froment and K. B. Bischoff), the strong point of almost all these books is largely analysis and/or design, with but a few examples interspersed to illustrate the theories. Particularly noteworthy books are the entirely theoretical *Chemical Reactor Theory*, edited by L. Lapidus and N. R. Amundson, the two practically oriented volumes of H. F. Rase, and the introductory text of C. G. Hill, Jr. . All these books have many commendable features.

Industrially important reactions are predominantly heterogeneous, and the notable absence of a comprehensive and connected discussion of such systems provided the basic motivation for knitting them into a coherent theme in a single presentation. Further, we were struck by the preponderance of hypothetical and arbitrary examples in many current books; since such examples lack the impact we intend for our readers, we decided at the outset to incorporate, as far as possible, real and industrially relevant examples, both qualitative and quantitative. Thus the two volumes were

conceived and written. We believe that this attempt is unique and hope that it fulfills our objectives and meets the requirements of a wide cross section of readers. We also believe that this is one of the few sets of two volumes in which threads of analysis have been assiduously woven into a web of design and examples. Taken as a whole, they have no counterpart at present.

We have been acutely conscious that these volumes have taken an unusually long time to write, and have undergone revisions during which their contents have seen drastic changes, including realignment of chapters. These changes were a result of newer knowledge that became available as well as the increasing store of research, industrial, and consulting experience of the authors. Our keen desire to include information concerning the translation of laboratory data into commercial plants, albeit in a limited way, has also contributed significantly to the writing time. During this period both of us have had the pleasure of contributing research papers and state-of-art reviews in just about all the subjects that we have covered in the 35 chapters that make up the two volumes.

The main theme of these volumes is: how to dissect the often complex problems relating to the interaction between diffusion and chemical reaction into tractable parts through a systematic analysis and a rational process-design strategy. To buttress this approach we have given a surfeit of qualitative and quantitative examples.

More than ten heterogeneous systems have been considered in these volumes. Volume 1 deals essentially with systems in which a solid phase appears either as catalyst or as a reactant; the second reactant is a gas or a solid, but one case of a system in which the second reactant is a liquid (the immobilized enzyme system) has also been included, in view of the similarity of approaches. Volume 1 comprises 21 chapters, of which 17 pertain to gas-solid (catalytic) reactions. The eighteenth chapter includes some special reactors such as those for supported liquid-phase catalytic systems, polymer-bound catalytic systems, and immobilized

enzyme systems. The next two chapters are devoted to gas–solid (noncatalytic) reactors and the one following is concerned with solid–solid reactions.

Volume 2 is concerned essentially with systems in which a liquid is involved as one of the reactants. The second reactant is either a gas or a liquid. In some systems the solid phase also appears, either as the second or third reactant or as a catalyst along with gas and liquid (slurry or trickle-bed reactors). The fourteen chapters comprising this volume cover fluid–fluid reactions; reactions with one gas and two liquid-phase reactants; simultaneous absorption and reaction of two gases; desorption with chemical reaction; simultaneous absorption and desorption with reaction; complex reactions; use of models in the simulation and design of reactors; solid–liquid reactions; reactions in fluid–fluid–solid systems; and solid-catalyzed fluid–fluid reactions. An extensive chapter is included to give pertinent details of a variety of contactors that are used for the reaction systems considered. An attempt has also been made to guide readers in selecting a contactor for a specified duty.

Although practically all industrially important heterogeneous systems are covered in the two volumes, three systems, namely, gas–solid (catalytic), gas–liquid and liquid–liquid, have received greater attention not only because they are truly ubiquitous but also because of the authors' greater personal involvement with these systems than with others.

The contents of the two volumes have been used for undergraduate and graduate courses in many countries. They have also been used for short intensive courses presented both in India and abroad. In addition, a wide cross section of chemical engineers and technologists have made valuable suggestions that have been incorporated.

These volumes are addressed not only to students of chemical engineering, chemical technology, and applied chemistry, but also to researchers, designers, and practicing engineers. We believe that all such readers of these volumes will find some directly useful material. We also believe that our coverage of the English-language literature up to 1981 is reasonably complete. We have made every effort to include literature from all over the world, but our lack of knowledge of Russian and Japanese prevented a fuller coverage of papers in these languages. We have covered some references that appeared in 1982 as well.

In some parts of these volumes, readers may discern an almost encyclopedic approach. While conceding such a disposition in selected areas, we would like to emphasize our main approach: we have cited in most

parts of these books only those references which are necessary in building up a comprehensive structure for each system, but in doing so we have not denied the reader the advantage of references that might not be directly relevant but that can be usefully consulted if needed. The approach is not that of a standard textbook but rather that of an advanced treatise.

In a comprehensive effort of this kind there is a temptation to adopt a unified approach to all systems. We quickly discovered the severe limitations of such an effort and decided to adopt prevalent approaches to different systems. For example, in Volume 1 we use the concept of effectiveness factor, which denotes the effect of diffusion on reaction, while in Volume 2 we continue with the practice of using the enhancement factor, which denotes the effect of reaction on diffusion. It would perhaps have been possible to adopt a common approach, for example, one based on effectiveness factor, for all systems; but doing so would have made the volumes less useful and appealing to readers than we believe it is in the present form. In pursuit of this approach we have also adopted different systems of nomenclature for Volumes 1 and 2 consistent with the more commonly used notation, and these are clearly defined at the beginning of each volume; uncommon notation usually acts as an irritant and makes the reader wary. The choice of units presented another vexing problem, and after considerable thought we decided to adopt widely used units in preference to the SI units.

We have both drawn heavily from our students and associates in writing these volumes. Their attachment to this venture has been a source of great strength to us. It would not be possible for us to place on record our gratitude to all of them individually, but each of us would like to particularly thank a few co-workers who have toiled to help us complete this voluminous and ambitious document. Most of them have witnessed with mute sympathy the protracted evolution of this venture and share our relief at its completion.

LKD would like to thank B. D. Kulkarni for his invaluable assistance, always rendered cheerfully; without his continued help the author doubts if Volume 1 could ever have been completed. Kulkarni has assisted in many ways, such as literature search, careful editing, and stimulating discussions on various aspects of Volume 1. The author is also grateful to many of his other students and colleagues who have rendered willing assistance: R. V. Choudhary, V. R. Choudhary, R. K. Irani, V. K. Jayaraman, N. G. Karanth, S. D. Prasad, P. C. Prasanna, N. S. Raghavan, R. A. Rajadhyaksha,

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We would like to express our gratitude to our wives Rajalakshmi and Sudha for having put up with our bursts of writing over a painfully long period of time and for mercifully refraining from expressing what

they must undoubtedly have felt—that these volumes were never going to be completed! The satisfaction of not letting them down marks a particularly pleasing conclusion to an arduous undertaking.

Both of us profusely thank Professor Octave Levenspiel and Professor Peter Danckwerts for their sustained interest, constructive comments, and encouragement. Professor Danckwerts' advice, "Let the good not be the enemy of the best," made a deep impression on us, and it is in this spirit that we present these volumes to our readers.

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January 1983*

To my wife

Rajalakshmi

*In whom simplicity, pure and elemental,
and courage, beautifully concealed,
combined to form the quintessence of life*

*Whose unspoken inspiration
sustained me through the
protracted evolution of the book—
the completion of which
I am not destined to share with her.*

L.K.D.

Notation

A	=	reactant species	$A_{i,j}$	=	elements of the matrix defined by Eq. 7.3
Al, Bl, \dots, il	=	adsorbed complexes of species A, B, \dots , i	$A'_{i,j}$	=	matrix defined by Eq. 7.4
A	=	general notation for a constant; or total area, cm^2 ; or group of variables	A_{\max}	=	parameter defined in Fig. 12.18
$\hat{A}_{i-1,j}$	=	parameter defined by Eq. 11.56	A_p	=	surface area of a single pellet, cm^2
A'	=	group defined by Eq. 12.24 and Eq. 17.7	A_{p0}	=	surface area of a single pellet at time zero, cm^2
A''	=	group defined in Eq. 11.64	A_r	=	surface area of reactor, cm^2
A_a	=	area of the aperture in Fig. 4.3	A_s	=	surface area per unit length, cm^2/cm
A_{bA}, A_{bB}, \dots	=	surface areas of particles A, B, \dots in Chapter 21, cm^2	$A_{s,e}$	=	effective contact area, cm^2
A_c	=	cross-sectional area of reactor, cm^2 ; or area of the cloud phase in Chapters 13 and 14; or area of contact in Chapter 21	A	=	parameter defined by Eq. 13.37
A_f	=	frequency factor in Arrhenius equation, sec^{-1}	\mathcal{A}	=	agitation parameter, cm/sec
$A_{f,cb}$	=	Arrhenius parameter for the carbon burning reaction	a	=	general symbol for a constant; or gas-solid interfacial area, cm^2/cm^3 ; or half the molecular size in Eq. 3.34; or initial concentration of solid in Chapter 21
$A_{f,f}$	=	Arrhenius frequency factor for the fouling reaction	a'	=	gas-solid interfacial area, cm^2/g
A_{fp}	=	Arrhenius frequency factor, $\text{mol}/\text{cm}^3 \text{ atm sec}$ or $\text{mol}/\text{g atm sec}$	a_b	=	area of bubble per unit volume, cm^2/cm^3
A_{fs}	=	Arrhenius frequency factor for sintering	a_e	=	area of emulsion per unit volume, cm^2/cm^3
A_h	=	heat transfer area per unit length of reactor, cm^2/cm	a_h	=	heat transfer area per unit volume of reactor, cm^2/cm^3
A'_1	=	parameter defined by Eq. 11.81	a_{ij}	=	sum of the products of residuals of i th and j th responses in Chapter 2

General Note. Usually symbols occurring at least once are clearly defined in the text and are included in the Notation section. Such symbols are included only if they are considered sufficiently important. For each letter of the alphabet (for example, A) the following order is used: (a) roman capital, A; (b) italic capital, *A*; (c) italic

lowercase a ; (d) bold face, **A**; (e) script capital, \mathcal{A} . Under each of these the order of presentation is alphabetic with respect to the subscripts. Superscripts such as prime, hat, half moon, and so on, on any alphabet are not singled out and are included in the alphabetic order based on subscripts.

a_j	= jet-emulsion contact area, cm^2/cm^3	C_A, C_B, \dots	= concentration of A, B, \dots , mol/cm^3
a_p	= area per unit volume of pellet, cm^2/cm^3	$\hat{C}_A, \hat{C}_B, \dots$	= dimensionless concentration of species A, B, \dots (C_A/C_{As} , $C_B/C_{Bs}, \dots$)
B	= reactant or product species;	C_A^*, C_B^*, \dots	= equilibrium concentration of A, B, \dots , mol/cm^3
$(Bi)_b$	= Biot number for heat transfer based on radiant heat transfer coefficient	C_{Ab}, C_{Bb}, \dots	= concentration of A, B, \dots in the fluid bulk, mol/cm ; or concentration of A, B, \dots in the bubble phase, mol/cm
$(Bi)_h$	= Biot number for heat transfer, $h_{fp}R/k'_e$ or $hd_p/2k'_e$	$\hat{C}_{Ab}, \hat{C}_{Bb}$	= dimensionless concentration of species A, B
$(Bi)_h^0$	= static contribution to Biot number for heat transfer, $h_e^0 d_p/2k'_e$	C_{Ac}, C_{Bc}	= concentration of A, B in the cloud phase, mol/cm^3
$(Bi)_h^*$	= Biot number for heat transfer, defined as $h_w^* d_p/2k'_e$	C_{Ae}, C_{Be}, \dots	= concentration of A, B, \dots in the exit stream, mol/cm^3 , or concentration of A, B, \dots in the emulsion phase, mol/cm^3
$(Bi)_m$	= Biot number for mass transfer, $k_g R/D_e$ or $k_g d_p/2D_e$	C_{Ai}, C_{Bi}, \dots	= concentration of A, B, \dots at the interface, mol/cm^3
$(Bi)_w$	= Biot number for wall heat transfer, $h_w R/k'_e$ or $h_w d_p/2k'_e$	\hat{C}_{Ai}	= dimensionless concentration of species A at the interface
B	= general notation for a constant; or group of variables; or multicomponent diffusion parameter defined by Eq. 4.91	C_{Ai}, C_{Bi}, \dots	= concentration of adsorbed species A, B, \dots on the catalyst surface, mol/cm^3
\tilde{B}	= parameter defined by Eq. 11.56	\hat{C}_{Ai}	= dimensionless concentration of species A at the interface
B'	= group defined by Eq. 12.24 and Eq. 17.14	C_{Ai}, C_{Bi}, \dots	= concentration of adsorbed species A, B, \dots on the catalyst surface, mol/cm^3
B''	= group defined in Eq. 11.64	$C_{A,ma}, C_{B,ma}, \dots$	= concentration of species A, B, \dots in the macropore, mol/cm^3
$B(\mathbf{k}, s)$	= Bayesian function in Chapter 2	$\hat{C}_{A,ma}, \hat{C}_{B,ma}$	= dimensionless concentration of species A, B in the macropore
b	= general symbol for a constant; or dilution ratio in Chapter 9	$C_{A,mi}, C_{B,mi}$	= concentration of species A, B in the micropore, mol/cm^3
b_0, b_1, \dots, b_6	= coefficients of Eq. 7.39	$\hat{C}_{A,mi}, \hat{C}_{B,mi}$	= dimensionless concentration of species A, B in the micropore
C	= chemical species	C_{As}, C_{Bs}, \dots	= concentration of A, B, \dots at the external surface of the catalyst, mol/cm^3
CF	= correction factor	$C_{As}(l)$	= local concentration of A on a catalyst plate at a distance l , mol/cm^3
CN	= cyclone number	\hat{C}_{Asb}	= ratio of surface to bulk concentrations C_{As}/C_{Ab}
C	= general term for concentration of any species, mol/cm^3	C_{A0}, C_{B0}, \dots	= inlet concentration of A, B, \dots to reactor, mol/cm^3
\hat{C}	= dimensionless concentration in pellet, C/C_s	C_{A0}^0, C_{B0}^0	= peak input pulse concentration of A, B, mol/cm^3
C''	= group defined in Eq. 11.64		
C*	= equilibrium concentration, mol/cm^3		
C_0	= inlet concentration to the reactor, mol/cm^3		
C_1, C_2	= intrinsic parameters for rate-model in Section 2.6.7		
$\overline{\Delta C}$	= confidence interval for concentration fluctuations (Eq. 13.38)		

C_b	= concentration in the fluid bulk, mol/cm ³ ; or concentration in the bubble phase, mol/cm ³	C_{pm}	= molar heat capacity of fluid, cal/mol°C
$C_{b,n}$	= concentration in bubble in the n th compartment, mol/cm ³	C_{ps}	= heat capacity of solid, cal/g°C
C_c	= concentration in the cloud phase, mol/cm ³	C_{p0}	= initial concentration of poison, mol/cm ³
C_{cp}	= center-plane concentration of fresh catalyst, mol/cm ³	C_s	= concentration of substrate in Chapter 18, mol/cm ³
\hat{C}_{cp}	= dimensionless center-plane concentration for fresh catalyst in Eq. 8.13	\hat{C}_s	= dimensionless concentration of substrate, C_s/C_{sb}
$(C_{cp})_f$	= center-plane concentration in a deactivated catalyst, mol/cm ³	C_{sb}	= concentration of substrate in the bulk, mol/cm ³ (Chapter 16)
$(\hat{C}_{cp})_f$	= dimensionless center-plane concentration in a deactivated catalyst in Eq. 8.13	C_{ss}	= concentration of substrate on the surface in Chapter 18, mol/cm ³
C_e	= exit concentration, mol/cm ³ ; or concentration in the emulsion phase, mol/cm ³	C_s	= concentration at the external surface of the catalyst, mol/cm ³
$C_{e,n}$	= concentration in emulsion in the n th compartment, mol/cm ³	C_t	= total concentration of gases, mol/cm ³
C_L	= concentration at length L (corresponding to exit), mol/cm ³ ; or concentration of active centers in Chapter 2, mol/cm ³ ; or concentration of active centers at $t = 0$ in Chapter 8, mol/cm ³	C	= cost factor
C_{Lt}	= concentration at the end of the dilute phase, mol/cm ³	C_a	= cost due to catalyst aging
C_l	= concentration of vacant sites at time t , mol/cm ³	C_r	= fixed-interval replacement cost
C_p	= heat capacity of the fluid (gas), cal/g°C; or concentration of poison in Chapters 8 and 16, mol/cm ³	C_T	= total operating cost due to catalyst
\bar{C}_p	= average heat capacity of the fluid, cal/g°C	\bar{C}_T	= average total cost per unit time
C_{pe}	= heat capacity of fluid at reaction equilibrium, cal/g°C	\bar{C}_{Tm}	= optimum total operating cost
C_{pf}	= heat capacity of fluid at frozen conditions, cal/g°C	c	= dimensionless concentration in the reactor
C_{pg}	= heat capacity of gas, used specifically when required to be distinguished from the heat capacity of solid, cal/g°C	\mathbf{c}	= vector of concentrations
		D	= chemical species
		Da	= Damköhler number, defined as kL/u or k_sR/D_e
		Da'	= local Damköhler number in Chapter 6; or any modified Damköhler number
		Da_G	= Damköhler number for reaction and diffusion in a grain
		DF	= dilution factor
		D	= general notation for diffusion coefficient, cm ² /sec; or group defined by Eq. 16.90
		\tilde{D}	= interdiffusion coefficient in the case of solid–solid diffusion, cm ² /sec
		$D(r_p)$	= diffusivity in a capillary of radius r_p , cm ² /sec

D_A, D_B, \dots, D_S	= diffusion coefficient of A, B, . . . , S, cm^2/sec ; or diffusivity of gas in solids A, B, . . . , S, respectively, in Chapters 19 and 20, cm^2/sec	$(D_e)_X, (D_e)_Y$	= effective diffusivities in catalysts X and Y, respectively, cm^2/sec
D_{AB}	= diffusion coefficient of A in B, cm^2/sec	D_g	= gas-phase diffusivity in Chapters 13 and 14, cm^2/sec
D_b	= bulk diffusivity, cm^2/sec	D_{ij}	= diffusivity of species j through stagnant i , cm^2/sec
D_{bA}, D_{bB}	= bulk diffusivity of species A, B, cm^2/sec	D_K	= Knudsen diffusion coefficient, cm^2/sec
D_c	= combined diffusivity, cm^2/sec	D_{KA}, D_{KB}	= Knudsen diffusion coefficient for species A, B, . . . , cm^2/sec
D_{cA}, D_{cB}	= combined diffusivity of species A, B, cm^2/sec	$D_{K,ma}$	= Knudsen diffusivity in macropore, cm^2/sec
D_{cd}	= configurational diffusivity, cm^2/sec	$D_{K,mi}$	= Knudsen diffusivity in micropore, cm^2/sec
D_e	= effective diffusivity, cm^2/sec	D_L	= liquid-phase diffusivity, cm^2/sec
$D_{eA}, D_{eB}, \dots, D_{eS}$	= effective diffusivity of A, B, . . . , S, cm^2/sec ; or effective diffusivity of gas in solids A, B, . . . in Chapters 19 and 20, cm^2/sec	D_l	= axial diffusivity, cm^2/sec
$D_{eA,ma}, D_{eB,ma}$	= effective diffusivity of species A, B in macropore	D_M	= molecular diffusivity, cm^2/sec
$D_{eA,mi}, D_{eB,mi}$	= effective diffusivity of species A, B in micropore	D_{ma}	= bulk diffusivity in macropore, cm^2/sec
D_{eb}	= effective bulk diffusivity, cm^2/sec	D_{mi}	= bulk diffusivity in micropore, cm^2/sec
D_{ebA}, D_{ebB}, \dots	= effective bulk diffusion coefficient for species A, B, . . . , cm^2/sec	D_p	= plate diameter in Chapter 13, cm
D_{eG}	= effective diffusivity of gas in a grain in the pellet, cm^2/sec	D_r	= radial diffusivity, cm^2/sec ; or diffusivity based on predominating pore radius
D_{eK}	= effective Knudsen diffusion coefficient, cm^2/sec	D_S	= surface diffusion coefficient, cm^2/sec
D_{eKA}, D_{eKB}, \dots	= effective Knudsen diffusion coefficient for A, B, . . . , cm^2/sec	D_{in}	= divergence between estimates of objective function for competing models
D_{el}	= effective axial diffusivity, cm^2/sec	d	= decay order; or exponent in Eq. 14.23
$D_{e,ma}$	= effective diffusivity in the macropore, cm^2/sec	d_b	= bubble diameter, cm
$D_{e,mi}$	= effective diffusivity in the micropore, cm^2/sec	d_{bm}	= maximum bubble diameter, cm
D_{ep}	= effective diffusivity of poison, cm^2/sec	d_{b0}	= initial bubble diameter, cm
D_{er}	= effective radial diffusivity, cm^2/sec	d_{dl}	= diameter of dip-leg, cm
D_{eS}	= effective diffusivity for, or including, surface transport	d_e	= effective diameter of packed column, cm; or equivalent bubble diameter in a reactor with internals, cm
		d_o	= outer diameter of horizontal immersed tube, cm
		d_{or}	= diameter of orifice, cm
		d_{pa}	= diameter of packing, cm
		d_t	= tube diameter
		E	= activation energy, kcal/mol; or a quantitative measure of the

	stoichiometric presence of a second reactant in estimating the effectiveness factor, Section 4.5.1			size in the inlet, outlet, and elutriation streams, respectively
$E(t)$	= residence time distribution function	F_w	=	mass flow rate, g/sec
E'	= entrainment rate	f	=	a function; or fugacity coefficient
E^*	= elutriation constant	$f(\mathbf{x}_m, \mathbf{k})$	=	rate predicted by the model
\tilde{E}	= enzyme concentration, mol/cm ³	f_a	=	free area of grid plate
\tilde{E}_0	= initial enzyme concentration, mol/cm ³	f_B	=	void fraction of the packed bed
E_a	= apparent (observed) activation energy, kcal/mol	f_{bed}	=	used specifically for f_B in Chapter 20 to distinguish from the general nomenclature f_i , which stands for porosity of species i
E_b	= activation energy for the reverse step	f_c	=	void fraction of the catalyst pellet
E_c	= efficiency of fluidized-bed contact	f_e	=	fraction of total active area that constitutes the external surface
E_d	= activation energy for diffusion, kcal/mol	f_f	=	porosity of the fluidized bed
E_f	= activation energy for the fouling step	f_{fp}	=	voidage of the bed with unflooded packing
		f_g	=	void fraction of catalyst particle occupied by gas in Chapter 18
$E_1^*(h)$	= $-Ei(-h) = \int_h^t \frac{e^{-t}}{t} dt$ is the exponential integral	f_i	=	fraction of the total area that constitutes the internal surface
		f_j	=	fraction of total sites in the j th patch
E_r	= reactor efficiency	f_{kj}	=	predicted rate in j th experiment using k th model
E_s	= activation energy for surface diffusion, kcal/mol; or activation energy for sintering in Chapter 19	f_l	=	void fraction of catalyst pellet occupied by liquid in Chapter 18
$E(t)$	= exit-stream age distribution	f_{ma}	=	voidage due to macropores
E_s^*	= specific elutriation constant	f_{mi}	=	voidage due to micropores
FN	= fouling number, defined by Eq. 8.40	f_{mf}	=	voidage of the fluidized bed at incipient fluidization
Fr	= Froude group, defined as $u^2/g d_b$; or $u_{or}^2/g l_j$ when applied to jet	f_{min}, f_{max}	=	minimum and maximum bed voidage
Fr'	= modified Froude group defined in Figure 13.5	f_p	=	void fraction of the particle
		f_{ps}	=	ratio of volume of the particles moving with the bubble to the volume of the bubbles
F	= molar feed rate, mol/sec; or represents a function	f_{pa}	=	porosity of the packing, that is, voidage of an empty packed bed in a packed fluidized bed
$F(r_p)$	= pore size distribution function	f_s	=	volume fraction of the solid
F_{Ms}	= molal flow rate of solids per unit area of reactor, mol/cm ² sec	f_w	=	volume fraction of wake
F_R	= recycle ratio	G	=	mass velocity, g/cm ² sec; or parameter defined by Eq. 8.76
F_s	= circulation rate of solids, g/sec; or weight rate of feed, g/sec	G'	=	group defined by Eq. 4.67
$F_{s,0}, F_{s,1}, F_{s,2}$	= quantity of material of a given			

ΔG	= change in free energy or chemical potential per mole of new phase, kcal/mol				trol fluid, cal/sec cm ² °K or kcal/hr m ² °K
$\Delta G'$	= free energy of activation per mole of nucleus growth, kcal/mol		h_c	=	heat transfer coefficient due to conduction, cal/sec cm ² °K or kcal/hr m ² °K
$G(C_{As}, T_s)$	= a function of surface concentration and temperature as defined by Eq. 11.43		h_{bs}	=	radiant heat transfer coefficient between solid particles, cal/sec cm ² °K or kcal/hr cm ² °K
G_M	= molar flow rate of gas, mol/cm ² sec		h_{bv}	=	radiant heat transfer coefficient between voids, cal/sec cm ² °K or kcal/m ² hr °K
G_{mf}	= mass flow rate at minimum fluidization velocity, g/cm ² sec		h_e	=	effective heat transfer coefficient for one-dimensional model, cal/sec cm ² °K or kcal/hr m ² °K
G'_{mf}	= mass flow rate at minimum fluidization velocity in a packed fluidized bed, g/cm ² sec		h_e^d	=	dynamic contribution to effective heat transfer coefficient, cal/sec cm ² °K or kcal/hr m ² °K
g	= gravitational constant, cm ² /sec		h_e^o	=	static contribution to effective heat transfer coefficient, cal/sec cm ² °K or kcal/hr m ² °K
g_c	= conversion factor				
g_1	= constant defined by Eq. 11.81				
H	= group defined in Eq. 12.64; or Hamiltonian; or heat of reaction group defined by Eq. 12.2; or heat transfer group defined by Eq. 13.27; or the level differences in the calculation of the pressure drop in a fluid-bed reactor-regenerator system		h_{fc}	=	heat transfer coefficient depicting the influence of fluid flow on conduction, cal/sec cm ² °K or kcal/hr m ² °K
H'	= group defined by Eq. 4.67		h_{fp}	=	fluid-particle heat transfer coefficient, cal/sec cm ² °K or kcal/hr m ² °K
ΔH	= heat of reaction, kcal/mol		h_{max}	=	maximum heat transfer coefficient, cal/sec cm ² °K or kcal/hr m ² °K
$\Delta H'$	= heat of reaction, kcal/g		h_{pc}	=	heat transfer coefficient for particulate motion as defined in Eq. 13.28, cal/sec cm ² °K or kcal/hr m ² °K
$H(C_{As}, T_s)$	= function of surface concentration of A and temperature defined by Eq. 11.43		h_s	=	surface diffusion parameter defined by Eq. 4.86
h	= general term for heat transfer coefficient, cal/sec cm ² °K or Planck's constant, J/sec		h_w	=	heat transfer coefficient at the wall, cal/sec cm ² °K or kcal/hr m ² °K
h_0	= a constant characteristic of the grid distributor, the height at which the bubble diameter is zero, cm		h_w^d	=	dynamic contribution to heat transfer coefficient at the wall, cal/sec cm ² °K or kcal/hr m ² °K
h_a	= heat transfer coefficient due to convection, cal/sec cm ² °K or kcal/m ² hr °K		h_w^*	=	heat transfer coefficient across a true fluid boundary layer, cal/sec cm ² °K or kcal/m ² hr °K
h_b	= radiant heat transfer coefficient, cal/sec cm ² °K or kcal/m ² hr °K		h_{wt}^d	=	total dynamic contribution to heat transfer coefficient at the wall, cal/sec cm ² °K or kcal/hr m ² °K
h_c	= heat transfer coefficient of con-				

I	= integral along the slug surface in Fig. 14.12; or intensity of segregation	K_f	= overall rate constant group, defined as $K'_f L_f/u_b$ for the fluidized bed (Eq. 14.13)
I_A, I_B	= impulse functions in Eq. 12.52	K'_f	= overall rate constant defined in Eq. 14.12
I_0	= distance of separation between particles A and B within which they react	K''_f	= group defined by Eq. 14.25
J	= integral associated with the cloud (Eq. 14.31 and Fig. 14.3); or group defined by Eq. 11.60	K_m	= dimensionless mass transfer group defined in Eq. 14.27 as $k_{0b} a_b L_f/u$ or $K_{0b} L_f/u$; or Michaelis–Menten constant in Chapter 18
J_p	= jet penetration, cm	K'_m	= apparent Michaelis–Menten constant
j_d	= mass transfer factor defined by Eq. 6.2	K_0	= dimensionless group defined as $K_v L_0/u$ or $k_p PW/F$
j_h	= heat transfer factor defined by Eq. 6.2	K'_0	= group defined by Eq. 14.26
K	= general constant; or equilibrium constant; or group defined by Eq. 8.29; or a consolidated adsorption constant defined by Eq. 4.64c; or multiple of half-particle diameter in the cell model	K_{0b}	= rate group defined as $k_{0b} a_b$, sec^{-1}
K'	= overall constant defined as the sum of the resistances in Eq. 14.34 as $\left(\frac{1}{K_m} + \frac{1}{K_0(1-\delta)}\right)^{-1}$	K_{0r}	= dimensionless group defined as $k_v L_{mf}/u = k_v C_{A0} L_{mf}/u$
K''	= effective rate constant, defined as $(k_v \rho_s W_e)$	K'_R	= overall constant for the successive contact model defined as $K' + K_b + K_d$ in Eq. 14.33
K_1, K_2	= rate groups defined by Eq. 16.18 and 16.19	K_{we}	= mass transfer coefficient between the wake and emulsion, sec^{-1}
K_A, K_B, \dots, K_i	= equilibrium constant for species A, B, \dots, i , atm^{-1} or cm^3/mol	k	= general representation for rate constant; or stage in a series; or general representation of model parameters such as k, k_A, \dots
K_b	= dimensionless reaction group defined in Eq. 14.27	k^p	= pore inclination constant used in the Johnson–Stewart model
K_{bc}	= gas interchange coefficient between bubble and cloud, sec^{-1}	k^0	= general notation of constant at time zero, sec^{-1}
K_{bc}	= gas interchange coefficient between bubble and emulsion, sec^{-1}	\hat{k}	= dimensionless rate group defined as $d_p A_f/u$ in Eqs. 11.57 and 11.58
$K_{bc,n}$	= bubble–emulsion mass transfer coefficient in the n th compartment sec^{-1}	\check{k}	= parameter related to rate constant (e.g., in Eq. 20.29), sec
K_{ce}	= gas interchange coefficient between cloud and emulsion, sec^{-1}	k_a	= observed rate constant, cm/sec or sec^{-1}
K_d	= dimensionless reaction group for the dilute phase defined in Eq. 14.27	k_b	= bubble-side mass transfer coefficient in a fluidized bed, cm/sec or Boltzmann constant, $\text{cal}/^\circ\text{K}$
		k_{bc}	= interchange coefficient between bubble and cloud phase, cm/sec

k_{be}	= interchange coefficient between bubble and emulsion phases, cm/sec	$(k'_{er})_{pr}$	= lateral thermal conductivity in a packed fluidized bed with horizontal flow, cal/cm sec °K or kcal/m hr °K
k_{cb}	= rate constant for carbon burning, cm ³ /mol sec	k_f	= general notation for rate constant for the fouling reaction, sec ⁻¹
k_{cbp}	= rate constant for carbon burning, 1/sec atm	k_g	= phenomenological mass transfer coefficient, cm/sec
k_{ce}	= interchange coefficient between cloud and emulsion phases, cm/sec	k_{gp}	= mass transfer coefficient expressed in partial pressure units, mol/cm ³ atm sec
k_d	= rate constant for deactivation, sec ⁻¹	k_{gr}	= mass transfer coefficient in the presence of chemical reaction, cm/sec
k_e	= emulsion-side mass transfer coefficient in a fluidized bed, cm/sec	k_{gv}	= volume-based mass transfer coefficient (= $k_g a$), cm/sec
k'_e	= effective thermal conductivity of the packed bed, cal/cm sec °K or kcal/m hr °K	k_j	= equilibrium constant for species A on patch J
$k_e^{\prime 0}$	= static contribution to the effective thermal conductivity, ($k'_{er}{}^0$ and $k'_e{}^0$) cal/cm sec °K or kcal/m hr °K	k_{je}	= mass transfer coefficient from jet to emulsion, cm/sec
$k_{ea}^{\prime 0}, k_{eb}^{\prime 0}, k_{ec}^{\prime 0}$	= static contributions due to radiation, conduction, and convection, respectively, cal/cm sec °K or kcal/m hr °K	k_L	= liquid-solid mass transfer coefficient, cm/sec
$k_{ea}^{\prime d}, k_{ec}^{\prime d}$	= effective thermal conductivity accounting for the dynamic contributions to convection and conduction, respectively, cal/cm sec °K or kcal/m hr °K	k_l	= rate constant per active site
k_{eff}	= effective rate constant, sec ⁻¹	k_m	= modified rate constant, defined as k_v/ω
k'_g	= fluid thermal conductivity, cal/cm sec °K or kcal/m hr °K	k_{mw}	= rate constant based on weight of reactant consumed, cm ³ /g catalyst sec
k'_{el}	= effective axial thermal conductivity of the packed bed, cal/cm sec °K or kcal/m hr °K	k_{nf}	= rate constant for nucleus formation
$k_e^{\prime 0}$	= static contribution to effective axial thermal conductivity, cal/cm sec °K or kcal/m hr °K	$k_{n,r}$	= rate constant for n th order decay in Eq. 8.74 (cm ³ /mol) ^{$n-1$} sec ⁻¹
k'_{er}	= effective radial thermal conductivity of the packed bed, cal/cm sec °K or kcal/m hr °K	$k''_{n,r}$	= rate constant defined by Eq. 8.72, sec ⁻¹
$k_{er}^{\prime d}$	= dynamic contribution to effective radial thermal conductivity, cal/cm sec °K or kcal/m hr °K	k_{ob}	= overall mass transfer coefficient, including k_b and k_e , in a fluidized bed, cm/sec
$k_{er}^{\prime 0}$	= static contribution to radial effective thermal conductivity, cal/cm sec °K or kcal/m hr °K	k_p	= rate constant based on partial pressure, mol/g atm sec
		k'_p	= pellet conductivity, cal/sec cm °K
		k_{pv}	= rate constant based on partial pressure and volume of catalyst, mol/cm ³ atm sec
		k_r	= consolidated rate constant, defined as $k_v [(K+1)/K]$ for a reversible reaction, sec ⁻¹

k_{rs}	= consolidated rate constant based on surface $k_s[K/(K+1)]$, cm/sec		length of packed column), cm; or likelihood function in Chapter 2
k_s	= surface reaction rate constant, cm/sec	\hat{L}	= dimensionless length parameter, l/L
k_{sA}, k_{sB}, \dots	= surface reaction rate constants for species A, B, . . . on catalyst, cm/sec	L'	= factor accounting for increased path flow (tortuous flow)
k_{sp}	= surface rate constant for the poisoning reaction, cm/sec	L_c	= critical bed height in Eq. 14.70, cm
k'_s	= thermal conductivity of solids, cal/cm sec °K or kcal/hr m °K	L_c	= equilibrium line in the $T-x$ plots
k_v	= rate constant based on reactor volume, sec ⁻¹	L_f	= height of the fluidized bed, cm
k_v	= rate constant based on catalyst volume, sec ⁻¹ (has the units of rate if the concentration is expressed in dimensionless form; thus in Chapter 17 the units are mol/cm ³ sec)	L_{fb}	= total length of freeboard region, cm
k_{vA}, k_{vB}, \dots	= reaction rate constant for the species A, B, . . . , sec ⁻¹	L_h	= initial height of a fixed layer over the packing in a packed fluidized bed, cm
$(k_v)_A$	= rate constant for the geometry A, sec ⁻¹	L_i	= dimensionless distance of the reactant boundary from the center line in the case of pore-mouth poisoning
k_v^0	= rate constant at zero carbon content, sec ⁻¹ ; or maximum value of rate constant corresponding to uniform activity, sec ⁻¹	L_m	= locus of the maximum rates in the $T-x$ plots
\bar{k}_v	= volume-averaged rate constant, sec ⁻¹	L_{ma}	= macropore length, cm
\hat{k}_v	= dimensionless constant defined by Eq. 9.16	\hat{L}_{ma}	= dimensionless macropore length, L_{ma}/L
k_{ve}	= rate constant for reaction in the emulsion phase, sec ⁻¹	L_{mf}	= height of bed at minimum fluidization, cm
$k_{v,f}$	= rate constant for the fouling reaction, sec ⁻¹	L_{mi}	= micropore length, cm
k_{vs}	= rate constant at the temperature of the external surface, sec ⁻¹	\hat{L}_{mi}	= dimensionless micropore length, L_{mi}/L
k_{v0}	= rate constant at time zero	L_0	= height of fixed bed, cm
k_{v1}, k_{v2}, \dots	= rate constant based on catalyst volume for reaction step 1, 2, . . . , sec ⁻¹	L_p	= total length of pore, cm
k_w	= rate constant based on weight of catalyst, cm ³ /g catalyst sec	L_{p0}	= L_p at time zero, cm
\mathbf{k}	= vector of model parameters in Chapter 2	L_s	= length of slugging bed, cm
$\hat{\mathbf{k}}$	= linearized value of vector \mathbf{k}	L_t	= total height of fluidized bed, cm
L	= total length parameter (i.e.,	L_w	= horizontal distance traveled by particle (see design of cyclone), cm
		l	= length parameter, axial coordinate, cm; or depth of a plate, cm
		l^*	= dimensionless length defined by Eq. 20.9
		l_b	= height of the gas emanating from each perforation in a distributor, cm
		l_j	= length along the grid jet, cm
		l_{fb}	= length of freeboard region, cm

l_{ma}	= macropore length coordinate, cm	N	= Avogadro's number; or flux of diffusing component; or product nM appearing in Eq. 8.77; or group defined by Eq. 11.60
l_{mi}	= micropore length coordinate, cm	N_1, N_2	= groups defined by Eqs. 19.85 and 19.86
l_0	= height of the fixed bed over the nonoperating orifice in a fluidized bed	$\tilde{N}'_1, \tilde{N}'_2$	= groups defined by Eqs. 19.92 and 19.93
l'_0	= height of spouted bed over an operating orifice in a fluidized bed, cm	N_A, N_B	= flux of diffusing component A, B due to volume diffusion relative to the fluid mixture at a given point, mol/cm ² sec
l_p	= length of the pore, cm	N_A^0, N_B^0	= combined diffusion and flow fluxes for species A, B
\hat{l}_R	= axial length normalized with respect to radius ($= l/R$)	N_{Az}, N_{Bz}	= flux of components A, B in the z direction
l_s	= length of slug, cm	N_b	= flux of diffusing component due to volume diffusion relative to stationary coordinates, mol/cm ² sec
l_t	= distance between tube centers, cm	N'_b	= flux of a diffusing component due to volume diffusion relative to the fluid mixture at a given point, mol/cm ² sec
M	= molecular weight; or dimensionless adiabatic temperature rise $\Delta T/T_0$; or momentum of the jet defined in Chapter 13, g cm/sec; or number of radial stages in the cell model	N_{bA}, N_{bB}	= flux of diffusing component A, B due to volume diffusion with respect to stationary coordinates, mol/cm ² sec
M_A, M_B	= molecular weights of A, B	N_F	= flux due to forced flow, mol/cm ² sec
M_c	= molecular weight of carbon	N_{KA}, N_{KB}	= flux of diffusing component A, B due to Knudsen diffusion relative to stationary coordinates, mol/cm ² sec
M_g	= molecular weight of gas	N_{or}	= number of orifices per unit area
M_0	= initial molecular weight of the feed; or initial momentum, g cm/sec	N_s	= number of spirals traveled in a cyclone; or number of solid diffusion transfer units given by Eq. 16.48
M_p	= molecular weight of poison	N_t^0	= total flux inclusive of Knudsen, bulk, and forced flow transport, mol/cm ² sec
m	= general symbol for constants or exponents; or solid content of the bubble phase; or temperature parameter defined in Eq. 7.35; or catalyst loading in a slurry reactor, g/cm ³ of slurry	$N(q)$	= distribution function characterizing the heats of adsorption
m'	= fraction of catalyst in mixed reactor in Chapter 12; or micropore modulus for a first-order reaction	n	= exponent appearing in various equations; or order of reaction, or number of sites involved in adsorption; or n th cell or compartment;
m''	= micropore modulus for a second-order reaction		
m_1, m_2	= roots of Eqs. 5.52 and 14.6		
m_H	= modulus used as a parameter in Fig. 14.3		
m_i	= index of reaction given by Eq. 21.18		
m_n	= parameter defined by Eq. 9.36		

	or number of fractions in a poly-dispersed phase	p^*	= partial pressure of diffusing component at equilibrium, atm
n_a	= apparent (observed) reaction order	p_A, p_B, \dots	= partial pressure of species A, B, . . . , atm
n_{or}	= total number of orifices	p_A^*, p_B^*, \dots	= partial pressure of components A, B, . . . at equilibrium, atm
n_p	= number of cylindrical pores per unit external area	p_{As}	= partial pressure at the surface, atm
Pe_h	= general definition of Peclet number for heat transfer $d_t \rho_g c_p u/k'$	p_{cr}	= critical value of partial pressure, atm
$Pe_{hl}, Pe'_{hl}, Pe''_{hl}$	= axial Peclet numbers for heat transfer	p_{ij}	= likelihood ratio for competing models i, j defined by Eq. 2.29
$Pe_{hr}, Pe'_{hr}, Pe''_{hr}$	= radial Peclet numbers for heat transfer	p_m	= partial pressure at a hot spot or a point on the maxima curve, atm
Pe_m	= general definition of Peclet number for mass transfer $d_l u/D$	p_{nm}	= ratio of intrinsic rate of an n th-order reaction to that of an m th-order reaction
Pe'_m, Pe'_h	= Peclet number for mass and heat transfer based on the particle diameter $d_p u/D$ or $d_p \rho_g C_p u/k'$	p'_0	= lower limit of the partial pressure of reactant at the reactor inlet, atm
Pe''_m	= Peclet number based on interstitial gas velocity, $d_p u_i/D$ or $d_p u/f_B D$	p_0^l, p_0^u	= lower and upper limits of partial pressures of the reactant at the reactor inlet, atm
$Pe_{ml}, Pe'_{ml}, Pe''_{ml}$	= axial Peclet numbers for mass transfer	$p_0(k)$	= relative probability density function in Chapter 2
$Pe_{mr}, Pe'_{mr}, Pe''_{mr}$	= radial Peclet numbers for mass transfer	p_s	= partial pressure at the surface, atm
$(Pe''_{mr})_M$	= molecular Peclet number	Q	= volumetric flow rate, cm^3/sec
Pr	= Prandtl number, $C_p \mu/k'_g$	Q_b	= volumetric flow rate through the bubble phase, cm^3/sec
P	= total pressure, atm; or group defined by Eq. 5.20; or multivariate probability density function in Chapter 2	Q_{be}	= total gas exchange between bubble and emulsion phases, cm^3/sec
P_1	= dimensionless group defined as $k_{je} a_j A_c J_p/Q$	Q_c	= volumetric flow rate through the cloud phase, cm^3/sec
P_2	= dimensionless group defined as $k_{be} a_b A_c J_p/Q$	Q_e	= volumetric flow rate through the emulsion phase, cm^3/sec
ΔP_d	= pressure drop across the distributor plate, atm	Q_h	= total heat transferred, cal/sec
P_X, P_Y	= groups defined by Eq. 15.25	Q_{or}	= total volume flowing through the nozzle, cm^3/sec
P, P_1, P_2	= profit functions defined variously in Chapters 12 and 16	q	= heat of adsorption in Eq. 2.10, kcal/mol; or number of responses in Chapter 2; or volumetric flow rate between bubble and emulsion phases, cm^3/sec
p	= probability; or partial pressure, atm; or pressure differential across any two points, atm; or degree of poisoning		
\tilde{p}	= perimeter of the reactor tube		