

CHEMICAL REACTOR DESIGN FOR PROCESS PLANTS

Volume Two: Case Studies and Design Data

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NOMENCLATURE

Units are described by the following symbols:

H = thermal energy	t = time
L = length	T = temperature
M = mass	

A	frequency factor, units same as corresponding rate constant
A, B, ...	reactants
A_c	cross-sectional area, L^2
A_D	acceptable percentage deviation of rate from that at wall
A_f	absorption factor, dimensionless, see Eq. 14.55
A_h	heat-transfer surface, L^2
$a, b, c, \dots, r, s, \dots$	stoichiometric coefficients
$a, b, c, \dots, r, s, \dots$	exponents in rate equations and various constants
a_A, a_B, a_C, \dots	activities of indicated components
a_c	external surface area of catalyst per unit volume of slurry, L^{-1}
a_m	external surface area of catalyst per unit mass, $L^2 M^{-1}$
a_p	external surface area of an average particle, L^2
a_s	geometric surface area per unit volume of particle, L^{-1}
a_t	total surface area of packing per unit volume of packed system, L^{-1}
a_V, a_v	surface area of dispersed phase (bubble or drop) per unit volume of system or expanded slurry and per unit volume of continuous phase, respectively, L^{-1}
a_w	wetted area of catalyst particle per unit mass of catalyst, $L^2 M^{-1}$
a_{WR}	surface area per unit volume of screen wire, L^{-1}
B	$E/R'T_j^2$ or $E/R'T_w^2$
b_{ch}	width of channel between plates, L
b_{ck}	thickness of coke, L
b_I	mass of inert packing per mass of catalyst
b_s	screen thickness, L
b_v	volume of inert packing per unit volume of catalyst
b_w	wall thickness, L

C	concentration, (moles) L^{-3}
C^\ddagger	concentration of activated complex, (moles) L^{-3}
$C_A, C_B, \dots, C_R, C_S$	molar concentration of indicated component, (moles) L^{-3}
C_A^*	concentration of A in bulk liquid at chemical equilibrium, (moles) L^{-3}
$C_A', C_B', \dots, C_R', C_S'$	moles of indicated component adsorbed per unit mass, (moles) M^{-1}
C_A''	concentration of A at beginning of poisoned zone, (moles) L^{-3}
C_{A_a}, C_{B_b}, \dots	molar concentration of indicated component in indicated phase <i>a</i> or <i>b</i> , (moles) L^{-3}
C_{B_b}	molar concentration of B in bulk liquid, (moles) L^{-3}
C_{B_d}	molar concentration of B in dispersed phase, (moles) L^{-3}
C_{B_c}	molar concentration of B in continuous phase, (moles) L^{-3}
$C_{A_e}, C_{B_e}, \dots, C_{R_e}, C_{S_e}$	effluent concentration of indicated component, (moles) L^{-3}
C_{A_f}, C_{B_f}, \dots	concentration of indicated component in feed, (moles) L^{-3}
C_{A_I}, \dots, C_{J_I}	concentration of indicated component inside catalyst particle, (moles) L^{-3}
$C_{A_i}, C_{B_i}, \dots, C_{R_i}, C_{S_i}$	molar concentration of indicated component at interface between two fluid phases, (moles) L^{-3}
C_{A_s}, C_{B_s}, \dots	concentration of indicated component at outer surface of catalyst, (moles) L^{-3}
C_D, C_{ds}, C_{dst}	drag constants (see Eqs. 13.19–13.23)
C_i'	concentration of vacant sites per unit mass, (moles) M^{-1}
c_d	loss coefficient for orifice, screen, or perforated plate
c_o	hopper cone angle correction (see Fig. 13.9)
c_p	heat capacity at constant pressure for mixture in mass units, $HM^{-1}T^{-1}$ (<i>f</i> superscript designates fluid when possibility for ambiguity exists)
$c_{p_A}, c_{p_B}, \dots, c_{p_R}, c_{p_S}$	molal heat capacity at constant pressure for indicated component, $H(\text{moles})^{-1}T^{-1}$
c_{p_a}	molal heat capacity at constant pressure of reaction mixture per mole of A fed, $H(\text{mole of A})^{-1}T^{-1}$
c_{p_F}	heat capacity of feed, $HM^{-1}T^{-1}$

c_{pI}	heat capacity of catalyst or other solid particle, $HM^{-1}T^{-1}$
c_{p_m}	molal heat capacity at constant pressure of mixture, $H(\text{moles})^{-1}T^{-1}$
c_v	molal heat capacity at constant volume, $H(\text{moles})^{-1}T^{-1}$
c_w	wall effect correction (see Eq. 13.15)
D	reactor or pipe inside diameter, L
D'	inside diameter in inches of reactor tube
\bar{D}	mean diameter of tube
D_{AB}, D_{BC}, \dots	bond energy for indicated bonds, $H(\text{mole})^{-1}$
D_c	diameter of coil, L
D_{ch}	diameter of channel, L
D_{ck}	inside diameter of cylinder of coke, L
\bar{D}_{ck}	mean diameter of coke cylinder, L
D_i	impeller diameter, L
D_H, D_H'	equivalent diameters for reactor jackets for heat transfer and pressure drop, respectively, L
D_j	diameter of jet, L
D_m	mean diameter of particles from screen or microscopic analysis, L
D_O	outside diameter of pipe or tube, L
\bar{DP}	degree of polymerization
D_p	diameter of a sphere having the same a_s as the particle in question, L
D_s	shaft diameter, L
\mathcal{D}	molecular diffusivity, L^2t^{-1}
$\mathcal{D}_A, \mathcal{D}_B, \dots$	molecular diffusivity of indicated component, L^2t^{-1}
\mathcal{D}_a	axial dispersion coefficient (axial diffusivity), L^2t^{-1}
\mathcal{D}_f	dispersion coefficient in dense phase of two-phase fluidized-bed model, L^2t^{-1}
$\mathcal{D}_{IA}, \mathcal{D}_{IB}, \dots$	effective diffusivity in the interior of catalyst particle for indicated component, L^2t^{-1}
\mathcal{D}_r	effective radial diffusivity in catalyst bed, L^2t^{-1}
d	diameter, L (d_1 = diameter of pipe jacket)
d_B	bubble diameter, L
d_c	diameter of cylinder, L
d_{ct}	outside diameter of coil tube, L
d_d	average drop diameter, L
d_{\max}	maximum drop diameter, L
d_{\min}	minimum drop diameter, L

d_p	diameter of a sphere having same surface area as particle in question, L
d_s	screen pore diameter, L
d_{sp}	diameter of sphere
d_v	diameter of sphere having same volume as particle in question, L
d_w	diameter of warp wire, L
E	energy of activation, $H(\text{mole})^{-1}$; prime indicates value for reverse reaction; subscript <i>obs</i> indicates observed value when intraparticle diffusional resistances are significant
E_B	fraction of bed that is effective
E_c	contactor efficiency
E_D	diffusional activation energy, $H(\text{mole})^{-1}$
E_F	fuel efficiency for generating facility
E_G	fractional point efficiency in plate tower
E_{mv}	fractional Murphee plate efficiency
E_p	polytropic efficiency
E_s	isentropic efficiency for compressor
E_T	energy dissipation per unit mass
E_t	turbine efficiency
E_z	energy necessary to separate two drops; see Eq. 15.13
EA	equilibrium approach, fractional approach to equilibrium
e, f, g, i, \dots	exponents in rate equations not necessarily the same as stoichiometric coefficients
F_A, F_B, \dots	molar feed rate of indicated component, $(\text{moles})t^{-1}$
F_e	outlet flow from reactor, $\text{moles } t^{-1}$
F_g	molar gaseous feed rate, $(\text{moles})t^{-1}$
F_L	molar liquid feed rate, $(\text{moles})t^{-1}$
F_{PU}	molar purge rate, $(\text{moles})t^{-1}$
F_Q	molar quench flow rate, $(\text{moles})t^{-1}$
F_r	molar recycle flow rate, $(\text{moles})t^{-1}$
F_T	total molar feed rate, $(\text{moles})t^{-1}$
$F(t)$	residence time distribution function (see p. 318 ¹)
$\mathcal{F}_A, \mathcal{F}_B, \mathcal{F}_j, \dots, \mathcal{F}_T$	moles of indicated component flowing per unit time at any position Z , $(\text{moles})t^{-1}$; T refers to total moles
f	friction factor for open pipe, dimensionless
f_A, f_B, \dots	fugacity of indicated component, atm
$f_A^\circ, f_B^\circ, \dots, f_j^\circ$	standard-state fugacity for indicated component (unity for gaseous systems), atm

f_e	initiator efficiency
f_g	friction factor for gas in fluidized bed or in pipe
f_k	friction factor for packed bed
f_p	particle friction factor in fluidized bed
f_w	wire area per gauze cross-sectional area
G	mass velocity, $Mt^{-1}L^{-2}$
G'	molar mass velocity, $(\text{moles})t^{-1}L^{-2}$
ΔG°	standard free energy of reaction, $H(\text{mole})^{-1}$
ΔG^\ddagger	free energy of activation, $H(\text{mole})^{-1}$; subscript L refers to standard state of pressure and temperature of system; subscript p refers to standard state at 1 atm
G_g	gaseous mass velocity, $Mt^{-1}L^{-2}$
G_I	insoluble or nonabsorbable (inert) gas mass velocity, $Mt^{-1}L^{-2}$
G_L	liquid mass velocity, $Mt^{-1}L^{-2}$
G_{mf}	mass velocity at minimum fluidization velocity, $Mt^{-1}L^{-2}$
G_p	solids superficial mass velocity, $Mt^{-1}L^{-2}$ (subscript <i>ch</i> designates velocity at choking conditions)
G_s	mass velocity in $\text{lb}/(\text{ft})^2 (\text{sec})$
g	acceleration due to gravity
g_c	force-mass conversion factor, $32.17 (\text{lb}_m \text{ft})/(\text{lb}_f \text{sec}^2)$ and $980.7 (\text{g}_m \text{cm})/(\text{g}_f \text{sec}^2)$
g_f, g_m	grams of force and grams of mass, respectively
H	actual enthalpy at pressure and temperature of systems, $H(\text{mole})^{-1}$, subscript (H_A, H_B, H_j, \dots) indicates component, or position
H^*	ideal gas enthalpy, $H(\text{mole})^{-1}$
ΔH°	standard heat of reaction, $H(\text{moles})^{-1}$
ΔH^\ddagger	enthalpy of activation, $H(\text{mole})^{-1}$
H_a	holdup for phase a or acid phase, volumes of a per unit volume of total mixture
$(\Delta H_A)_{T_1}$	heat of reaction at indicated temperature, per mole of A reacted, $H(\text{mole})^{-1}$
ΔH_a	heat of adsorption, $H(\text{mole})^{-1}$; primed value is differential heat of adsorption; <i>iso</i> indicates isotheric
H_b	holdup for b phase, volumes of b per total volume
H_D	head generated by impeller, $\text{ft lb}_f/\text{lb}_m$ or $\text{cm g}_f/\text{g}_m$
H_d	fractional volume or holdup of dispersed phase, volume of dispersed phase per unit volume of total mixture

$H_{f_A}^\circ, H_{f_B}^\circ, \dots, H_{f_j}^\circ$	standard heat of formation per mole of indicated component at 298°K, $H(\text{mole})^{-1}$
H_g	fractional gas holdup, volume of gas per unit volume of operating reactor volume
H_L	total liquid holdup fraction, volume of liquid per total volume
H_l	enthalpy loss per mass of oil flow, HM^{-1}
H_{OL}	operating fractional liquid holdup, volume of liquid per unit volume of operating reactor volume
ΔH_s	isentropic enthalpy change
ΔH_v	latent heat of vaporization
h	heat-transfer coefficient, $Ht^{-1}L^{-2}T^{-1}$
h	Planck's constant, 6.624×10^{-27} erg-sec per molecule
h_c	height of cylinder, L
h_G	gas heat-transfer coefficient, $Ht^{-1}L^{-2}T^{-1}$
h_g	liquid heat-transfer coefficient with sparging, $Ht^{-1}L^{-2}T^{-1}$
h_i	inside film coefficient of tube, $Ht^{-1}L^{-2}T^{-1}$
h_L	liquid heat-transfer coefficient, $Ht^{-1}L^{-2}T^{-1}$
h_l	liquid height on tray, L
h_o	outside film heat-transfer coefficient
h_s	heat-transfer coefficient between catalyst surface and surrounding fluid, $Ht^{-1}L^{-2}T^{-1}$
h_T	overall heat-transfer coefficient from position $r = R_b$ of bed to the jacket fluid, $Ht^{-1}L^{-2}T^{-1}$
h_w	wall heat-transfer coefficient, see page 406 ¹ Eq. 9.16, $Ht^{-1}L^{-2}T^{-1}$
h_w^s, h_w^f	wall heat-transfer coefficient for solid and fluid, respectively, $Ht^{-1}L^{-2}T^{-1}$
hp	horsepower
I, I	intercept and inert, respectively
$[I]_a$	carbonium ion concentration in acid phase
I_m	dispersed phase mixing modulus
J	mechanical equivalent of thermal energy, 778 ft-lb _f /BTU, 0.4267 kg _f m/cal; $1/J = 1.286 \times 10^{-3}$ BTU/ft-lb _f , 2.343 cal/kg _f m
J_D	J -factor for mass transport at catalyst surface, dimensionless (see Eq. 11.15)
J_h	J -factor for heat transfer at catalyst surface, dimensionless (see Eq. 11.16)
J_R	fraction of collisions that lead to reaction

J_w	jacket space, L (see Table 8.7)
j	any component
K	thermodynamic reaction equilibrium constant
K'	equilibrium constant for the surface reaction
K^\ddagger	thermodynamic equilibrium constant between reactants and activated complex in terms of activities, dimensionless
$K_A, K_B, K_R, K_S, \dots$	apparent adsorption equilibrium constants for the indicated reactants, atm^{-1} for gaseous components or $(\text{moles})^{-1}L^3$ when concentration is used in rate equation
K_b	concentration equilibrium constant for reaction in phase "b" (units depend on stoichiometry)
K_c	equilibrium constant in concentration units (units depend on stoichiometry)
K_c^\ddagger	concentration equilibrium constant between reactants and complex that does not include the partition function for the reaction coordinate
K_D, K_D°	dissociation constants for substituted and unsubstituted aromatic, respectively
$(K_d)_A, (K_d)_B$	distribution coefficients for indicated components, dimensionless
K_G	overall mass-transfer coefficients from bulk gas to bulk liquid phase in terms of partial-pressure driving force, $(\text{moles})t^{-1}L^{-2}(\text{atm})^{-1}$
K_L	overall mass-transfer coefficients from bulk gas to bulk liquid phase in terms of concentration driving force, Lt^{-1}
K_n	controller gain
K_p	equilibrium constant in partial-pressure units (units depend on stoichiometry)
K_{th}	diffuser throw constant (see Table 7.3)
K_v	vapor-liquid equilibrium constant, dimensionless
k	rate constant as designated at point of use or based on activities
k	Boltzmann constant, $1.3805 \times 10^{-16} \text{ erg}/(^{\circ}\text{K})$ (molecule)
$k_A, k_B, \dots, k_R, k_S, \dots$	adsorption rate constants for indicated components (desorption is indicated by prime), $(\text{moles})L^{-3}t^{-1}$ $(\text{atm})^{-1} [(\text{moles})L^{-3}t^{-1} \text{ for } k_A']$
k_a, k_b	reaction rate constants for multiphase reactions in a and b phases, respectively

$k_{aa}, k_{ab}, k_{ba}, k_{bb}$	copolymerization rate constants (see Eqs. 4.20 and 4.21)
k_c	reaction rate constant for rate equations involving concentration terms (prime indicates reverse rate constant), $(L^3/\text{moles})^{n-1}t^{-1}$
\hat{k}_c	same as k_c except per unit mass of catalyst, $L^{3n}(\text{moles})^{1-n}M^{-1}t^{-1}$
k_{ce}	same as k_c except based on exterior area of catalyst, $(\text{moles})^{1-n}L^{3n-2}t^{-1}$
k_{cs}	reaction rate constant in terms of total catalyst surface area, $(\text{moles})^{1-n}L^{3n-2}t^{-1}$
k_{cv}	reaction rate constant based on volume of catalyst and concentrations, $(\text{moles})^{1-n}L^{3n-3}t^{-1}$
k_d	rate constant for initiator dissociation
$k_{d0}, k_{d1}, \dots, k_{dm}$	deactivation rate constants, order indicated by second subscript, that is, k_{d1} = first-order deactivation constant
k_f	a concentration independent reaction rate constant for a gaseous reaction, units based on order
k_G	mass-transfer coefficient between bulk gas and gas-liquid interface, partial-pressure driving force, $(\text{moles})t^{-1}L^{-2}(\text{atm})^{-1}$
k_{gA}^s, k_{gB}^s	mass-transfer coefficient for indicated component between catalyst surface and surrounding fluid with pressure driving force, $(\text{moles})t^{-1}L^{-2}(\text{atm})^{-1}$
k_L	mass-transfer coefficient between bulk liquid and gas or liquid-liquid interface when reaction occurs, Lt^{-1}
k_L°	mass-transfer coefficient between bulk liquid and liquid-gas interface without reaction occurring, Lt^{-1}
k_n	rate constant for n th order reaction
k_O	apparent overall rate constant (see Eqs. 14.23 and 14.24)
k_p	reaction rate constant in terms of partial-pressure units; prime indicates reverse reaction, $(\text{moles})L^{-3}t^{-1}(\text{atm})^{-n}$; k_p^\bullet is value of k_p at outlet temperature
\hat{k}_p	reaction rate constant in terms of catalyst mass and partial pressures, $(\text{moles})M^{-1}t^{-1}(\text{atm})^{-n}$
k_{pr}	polymerization (propagation) rate constant
k_{ps}	reaction rate constant based on total surface area and partial-pressure units, $(\text{moles})L^{-2}t^{-1}(\text{atm})^{-n}$

k_{pe}	reaction rate constant based on exterior surface area of particle and in terms of partial pressures, (moles)(exterior surface area) ⁻¹ t ⁻¹ (atm) ⁻ⁿ
k_q	concentration independent rate constant for systems forming non-ideal solutions
k_s	surface reaction rate constant (prime is used for reverse reaction), units depend on order
k_{sA}, k_{sB}	mass-transfer coefficient between catalyst surface and surrounding fluid with concentration driving force for indicated component, Lt ⁻¹
k_t	reaction rate constant for termination
k_{tc}	rate constant for termination by combination
k_{tr}	rate constant for chain transfer
L	reactor length, or length of bed in a catalytic reactor or packed tower, L
LHSV	liquid hourly space velocity, (volumes liquid)(volume reactor) ⁻¹ t ⁻¹
L_A, L_B, L_C, \dots	flammability limit in percent of indicated component
L_B	equivalent length of one return bend
L_d	length of diffuser wall, L
L_e	equivalent length of tube, ft
L_K	thickness of flat plate, L
L_n	length of straight pipe, L
L_p	depth of pore, L
L_R	concentration of active sites, (moles) M^{-1}
l_l	impeller blade length
lb _f , lb _m	pounds of force and pounds of mass, respectively
t	symbol for an active site
l_{bp}	distance between baffles in jacket, L
l_s	scale of smallest eddies, L
M	monomer
M_A, M_B, M_j, \dots	molecular weight of indicated component
M_F	molecular weight of total feed
M_g	molecular weight of gas phase
M_I	molecular weight of inerts
M_m	molecular weight of mixture
\overline{M}_n	number average molecular weight
m	variously used as slope, constant, exponent, and deactivating event order
m_c	catalyst loading in slurry reactor per unit volume of expanded slurry, ML^{-3}
m_d	mass of monomer in drops, m

m_E	allowable entrainment, Mt^{-1}
m_H	Henry's law constant
m_o	oil flow rate, Mt^{-1}
m_s	mass of sample, M
m_{sf}	solids flow rate, Mt^{-1}
m_Z	rate of solids thrown into freeboard, Mt^{-1}
N	impeller revolutions per unit time, usually expressed as rpm
N_A, N_B, \dots	mass-transfer rate of indicated component, (moles) $L^{-2}t^{-1}$
N_A', N_B', \dots	mass-transfer rate, (moles) t^{-1}
N_{BO}	$(k_g)_p R_p / \mathcal{D}_{I_p}$, Biot number for poison precursor
N_{DA}	$(k_c)_p R_p / \mathcal{D}_{I_p}$, Damkohler number for poison
N_{Fr}	impeller Froude number, $N_2 D_1^2 / g_c$
N_{Kr}	Karlovitz number (see Eq. 10.32)
N_{Nu}	Nusselt number defined as used
N_o	Avogadro's number, 6.02252×10^{23} molecules/mole
N_p	power number, $P_a g_c / \rho N^3 D_1^5$
$(N_{Pe})_a$	axial Peclet number, $D_p u_s / \mathcal{D}_a$ for beds and Du / \mathcal{D}_a for empty tubes
$(N_{Pe})_r$	$D_p u_s / \mathcal{D}_r$, radial Peclet number
N_{Pr}	Prandtl number, $c_p \mu / \lambda_f$
N_{QR}	discharge coefficient, Q_R / ND_1^3
N_{Re}	Reynolds number, $D_p G / \mu$ for catalyst bed, DG / μ for empty tube; $\bar{d}_t u_{mf} \rho_g / \mu_g$ for fluidized bed at minimum fluidization velocity
$(N_{Re})_i$	impeller Reynolds number, $\rho ND_1^2 / \mu$
N_s	solid diffusion number, for poison $3\mathcal{D}_{I_p} L / R_p^2 u_i$ where \mathcal{D}_{I_p} is the effective diffusivity in particle of poison precursor
N_{Sc}	Schmidt number, $\rho \mu_f / \mathcal{D}_j$
N_{St}	Stanton number, $h / c_p G$
N_T	total number of trays
$N_z, N_\beta, N_\delta, N_\zeta$	dimensionless groups for fluidized bed (see Eqs. 13.30–13.33)
n	reaction order, also used to designate number of carbon atoms in a molecular formula
n_A, n_B, \dots, n_I	moles of indicated component (n_I refers to inerts)
$n_{A_n}, n_{B_n}, \dots, n_{I_n}$	moles of indicated component per mole of A fed (I refers to inerts)
n_{AF}, n_{BF}, \dots	moles of indicated component per total moles of total feed
n_b	number of impeller blades

n_{bv}	number of vertical baffles
n_{ch}	number of channels per unit cross section of bed, L^{-2}
n_I	number of equally spaced impellers
n_m	number of monomer units
n_r	number of reactors in series
n_s	number of gauzes or screens
n_{sg}	number of slugs per unit volume of fluidized bed
n_T	total moles in reaction mix or total moles per mole of A, n_{T_a} , or per total moles of feed, n_{T_F}
n_i^*	total moles per unit mass at equilibrium, (moles) M^{-1}
n_{tr}	moles of tracer added in pulse
n_w	mesh size of screen, (wires) L^{-1}
P	total pressure, atm or (force) L^{-2} , similar units for other pressure terms unless stated otherwise
ΔP	pressure drop
$\Delta P'$	pressure drop, <i>psi</i>
$P_A, P_B, P_j, \dots, P_R, P_S$	partial pressure for indicated component, atm; asterisk is used to indicate value at thermodynamic equilibrium; sub I indicates inerts
P_{As}, P_{Bs}	partial pressure of indicated component at catalyst surface, atm
P_a	agitator power, (force) $L t^{-1}$
P_{cr}	critical pressure
ΔP_d	pressure gradient due to drag
ΔP_D	distributor pressure drop
P_e	equivalent power (see Table 14.4)
ΔP_e	pressure drop due to sudden enlargement
P_f	pressure factor, $y_f P$
$(\Delta P_f)_p, (\Delta P_f)_g$	frictional pressure drop due to particles and fluid, respectively, in a fluidized bed
$\Delta P_G, (\Delta P/\Delta Z)_G$	pressure drop and gradient as if gas flowing alone
P_g	power dissipated in liquid by sparging, (force) $L t^{-1}$
P_k	power required to compress gas; see Eq. 14.10
$\Delta P_L, (\Delta P/\Delta Z)_L$	pressure drop and gradient as if liquid flowing alone
P_o	vapor pressure, atm
$\Delta P_{TP}, (\Delta P/\Delta Z)_{TP}$	two-phase flow pressure drop and gradient
p	steric factor in collision theory
p	impeller blade pitch
Q	volumetric flow rate, $L^3 t^{-1}$
Q_F	volumetric feed rate, $L^3 t^{-1}$

Q_g	volumetric gas flow rate, L^3t^{-1}
Q_L	volumetric liquid flow rate, L^3t^{-1}
Q_R	volumetric circulation rate in stirred tank or recycle rate, L^3t^{-1}
q	heat-transfer rate, Ht^{-1}
q_{diff}	differential heat of adsorption, $H(\text{mole})^{-1}$
q_g	heat generated, Ht^{-1} (prime indicates per mole of reactant basis)
q_i	heat flux based on inside surface area of tube, $HL^{-2}t^{-1}$
q_{iso}	isotheric heat of adsorption, $H(\text{mole})^{-1}$
q_o	heat flux based on outside surface area of tube, $HL^{-2}t^{-1}$
q_p	heat generation potential, dimensionless (see p. 285 ¹)
q_r	heat removed, Ht^{-1} (prime indicates per mole of reactant basis)
q_v	heat generated per unit volume of tube, $HL^{-3}t^{-1}$
q_{vw}	heat generated per unit volume of tube determined at wall temperature, $HL^{-3}t^{-1}$
q_z	heat flux per unit length, $HL^{-1}t^{-1}$
R, S, ...	products
R	gas-law constant in PVT units, 82.06 (cm ³)(atm)/(g mole)(°K), 0.08204 (liter)(atm)/(g mole)(°K), 10.731 (ft)(lb _f)/(in) ² (lb mole)(°R), or 0.7302 (ft ³)(atm)/(lb mole)(°R)
R'	gas-law constant in thermal units, 1.987 g cal/(g mole)(°K) or BTU/(lb mole)(°R)
R_1, R_2	reactivity ratios for copolymerization
R_B	radius of a bend, L
R_b	radius of bed, L
R_d	diffuser throat radius, L
R_{eff}	effective radius of agitation, L
R_j	rate of production of j in mass units, $ML^{-3}t^{-1}$
R_p	radius of spherical particle, L
R_q	$(dq_g/dT)/(dq_r/dT)$
\mathcal{R}_h	fouling factor
\mathcal{R}_p	resistance coefficient for pipe (see p. 421 ¹)
r	radial distance from center of bed, L
r_1, r_2, \dots	rates of reaction No. 1, No. 2, ...
$(-r_A)$	rate of disappearance of reactant A, (moles) $L^{-3}t^{-1}$
$(-\hat{r}_A)$	rate of disappearance of reactant A on a unit mass of catalyst basis, (moles) $M^{-1}t^{-1}$

$(-r_A)_a, (-r_B)_b$	rate of indicated component disappearance per unit volume of indicated phase
r_a	rate of adsorption, $(\text{moles})M^{-1}t^{-1}$
$(\Delta r_A)_P, (\Delta r_A)_T$	rate error caused by pressure and temperature uncertainty, respectively
$(-\hat{r}_A)_s$	rate of disappearance of A based on conditions at catalyst exterior surface, $(\text{moles})M^{-1}t^{-1}$
$(-r_B)_{so}$	mass of solid B consumed per unit time, Mt^{-1}
r_{ck}	rate of coke formation, $(\text{moles})L^{-3}t^{-1}$
r_d	rate of desorption, $(\text{moles})M^{-1}t^{-1}$
r_g	reaction rate in gas phase, $(\text{moles})L^{-3}t^{-1}$
r_I	radial distance from center of particle (or drop), L
(r_i)	rate of generation of new radicals (rate of initiation) $(\text{moles})L^{-3}t^{-1}$
r_L	rate of reaction in liquid phase
r_p	pore radius, L
r_{pr}	rate of polymerization (propagation), $(\text{moles})L^{-3}t^{-1}$
r_R, r_S, r_j	rate of formation of indicated product, $(\text{moles})L^{-3}t^{-1}$
r_{To}	combined rate in liquid and gas phase
r_t	rate of termination
ΔS°	standard entropy of reaction, $H(\text{mole})^{-1}T^{-1}$
ΔS^\ddagger	entropy of activation, $H(\text{mole})^{-1}T^{-1}$; subscript "L" refers to standard state of pressure and temperature of the system, and subscript "p" refers to standard state of 1 atm
ΔS_a	standard entropy of adsorption, $H(\text{mole})T^{-1}$
S_c	coil spacing, L
S_g	total surface area of a porous solid per unit mass, L^2M^{-1}
S_ℓ	slope
S_n	stoichiometric ratio of carbon burned per molecule of O_2 consumed
S_R, S_S	selectivity to desired product R and undesired product S (prime designates instantaneous value)
(SV)	space velocity, t^{-1} , defined as volumes or mass
s	number of equidistant centers surrounding each active site
T	temperature of reacting fluid, $^\circ K$ or $^\circ R$
T_b	bulk fluid temperature
T_{cr}	critical temperature
ΔT_{ck}	temperature drop across coke

$(\Delta T)_D$	temperature increase to double reaction rate
T_e	effluent or exit temperature
T_{eq}	equilibrium temperature
T_F	feed temperature
ΔT_f	temperature drop across film
T_h	throw, distance traveled from a diffuser to a point corresponding to a predetermined terminal velocity, feet
T_I	interior catalyst temperature
T_{iso}	isokinetic temperature
T_j	jacket temperature (temperature of cooling or heating medium)
ΔT_M	temperature difference between middle of reactor and wall
T_m	mixture or mean temperature as indicated
T_{op}	optimum temperature for maximum rate
T_0	inlet or initial temperature or base temperature
T_Q	quench temperature
T_r	reduced temperature
T_{R_b}	temperature in packed bed at $r = R_b$; superscripts f and s refer to fluid and solid, respectively
T_{reg}, T_{re}	temperatures in regenerator and reactor; respectively
T_s	exterior surface temperature of catalyst
T_w	tube wall temperature
ΔT_w	temperature drop across metal wall
T_x	temperature of coaxial gas (see Table 10.9)
t	time, t
t_b	batch mixing time, t
t_D	diffusion time, t
t_f	mixing time with flow but no agitation, t
t_{mix}	mixing time for CSTR, t
t_R	reaction time, t
t_s	time on stream, t
$t_{\Delta Z}$	contact time for length ΔZ , tL^{-1}
U	overall heat-transfer coefficient with driving force of difference between bulk mean reactor temperature and jacket fluid temperature, $H/t^{-1}L^{-2}T^{-1}$
$U_A, U_B, U_C, U_j, \dots$	internal energy of indicated component per mole, $H(\text{mole})^{-1}$
ΔU_A	internal energy of reaction per mole of A reacted, $H(\text{mole})^{-1}$

$U_{f_A}^\circ, U_{f_B}^\circ, U_{f_C}^\circ, \dots$	standard internal energy of formation at 25°C, $H(\text{mole})^{-1}$
U_v	overall volumetric coefficient of heat transfer, $HL^{-3}t^{-1}T^{-1}$
U_z	point value of overall heat-transfer coefficient, $Ht^{-1}L^{-2}T^{-1}$
U_0	point value in time of overall coefficient of heat transfer
u	velocity, Lt^{-1}
u'	shear rate, t^{-1}
u_1, u_2	upstream and downstream velocity, respectively, Lt^{-1}
u_B	bubble velocity, Lt^{-1}
u_b	burning velocity, Lt^{-1}
u_{ch}	superficial velocity of fluid at choking, Lt^{-1}
u_f	free settling velocity, Lt^{-1}
u_g	average linear velocity of gas phase in a fluidized bed or gas-liquid system, Lt^{-1}
u_i	interstitial velocity in a bed of catalyst, Lt^{-1}
u_j	jet velocity, Lt^{-1} (see Table 10.9)
u_m	critical minimum superficial velocity to maintain all distributor openings operative, Lt^{-1}
u_{mf}	superficial velocity at point of minimum fluidization velocity, Lt^{-1}
u_o	velocity through orifice or sparger hole velocity, Lt^{-1}
u_p	average linear velocity of particles, Lt^{-1}
u_s	superficial fluid velocity, Lt^{-1}
$(u_s)_g$	superficial gas velocity, Lt^{-1}
u_{sg}	slug velocity, Lt^{-1}
$(u_s)_L$	superficial liquid velocity, Lt^{-1}
u_{sl}	slip velocity, Lt^{-1}
u_{st}	saltation velocity, Lt^{-1}
\bar{u}_{st}	saltation velocity for mixed sizes, Lt^{-1}
u_t	terminal velocity, Lt^{-1}
u_{vn}	velocity of vapor based on net area of tower (cross-sectional area less downcomer cross section), Lt^{-1}
u_x	coaxial velocity, Lt^{-1} (see Table 10.9)
u_z	point velocity, Lt^{-1}
V	volume of reactor, L^3
V°	volume of gas adsorbed corrected to 0°C and 760 mm, L^3

V_a, V_b	fractional volumes of indicated phases, volume of phase/total volume of mixture
V_B	volume of bubble, L^3
V_i	volume of reaction mixture below slurry-liquid interface, L^3
V_k	volume of particle, L^3
V_L	liquid volume, L^3
V_m	volume of gas adsorbed as a monolayer corrected to 0°C and 760 mm, L^3
V_p	pore volume per unit mass of particle, $L^3 M^{-1}$
V_R	volume of reaction mix, L^3
V_{sg}	volume of slug, L^3
V_T	total aerated or expanded volume, L^3
v	specific molal volume, $L^3(\text{mole})^{-1}$
v^\ddagger	molal volume of activated state $L^3(\text{mole})^{-1}$
Δv^\ddagger	difference in molal volume between the activated state and the reactants, $L^3(\text{mole})^{-1}$
v_m	mean molal volume, $L^3(\text{mole})^{-1}$
W	mass of catalyst, M
W_a	actual work, $H(\text{mole})^{-1}$
W_d	width of flat diffuser, L
W_f	mass of fluid flowing per unit time, $M t^{-1}$
W_m	weight fraction of a given mass
$(-W_s)$	isentropic work, $H(\text{mole})^{-1}$
w	extent-of-reaction factor (see p. 174 ¹)
w_2	weight fraction of polymer in polymer-rich phase
w_l	impeller blade width, L
(w_l)	weight fraction initiator in monomer
w_{pr}	weight fraction of polymer in solution
w_x	weight fraction of size fraction x
X_A, X_R, \dots	moles of indicated component converted per mole of A charged or fed
X_A^*	equilibrium conversion of A
X_{AT}, X_{RT}, \dots	moles of indicated component converted per mole of total feed or charge
X_e	conversion at reactor discharge
X_I	conversion level at reactor inlet
X_0	conversion level in reactor feed or charge
x_A, x_B, \dots	mole fraction of indicated component in liquid phase
x_n	mole fraction in liquid from tray n

Y_C	fractional carbon remaining on catalyst, moles carbon remaining per mole carbon initially present
Y_G, Y_L	ratio of ΔP gradient for mixed phase to that for gas alone (G) or liquid alone (L) (see Fig. 14.8)
Y_R	yield of desired product R (prime designates instantaneous value)
$y_A, y_B, \dots, y_R, y_S$	mole fraction of indicated component in gaseous phase (subscript i = interfacial value, subscript e refers to effluent, subscript 0 refers to feed or inlet value)
y^+	mole fraction of a component in vapor in physical equilibrium with that component in liquid
y_b	mole fraction in rich gas entering bottom of tower
y_f	mole fraction factor for mass transfer, see Eq. 11.15, dimensionless
y_n	mole fraction of a vapor component from tray n .
y_l	mole fraction in lean gas leaving top of tower
Z	longitudinal distance along a reactor, L
Z''	length of poisoned zone in catalyst, L
Z_c	height of coil from tank bottom
Z_F	freeboard height, L
Z_i	height of impeller from tank bottom, L
Z_L	liquid height in a stirred or sparged vessel, L
Z_{mf}	height of bed at point of minimum fluidization velocity, L
Z_s	height of suspended solids, L
Z_{sg}	height of equivalent cylindrical slug having same volume as actual slug (see Table 13.8)
Z_T	distance between set of nozzles or height of chamber, ft (see Table 10.9)
Z_v	vertical distance between pressure taps, L
z	distance along film
z_m	compressibility factor for mixture

Greek Letters

α, β	various exponents and constants defined at point of use
α_a	projected area of molecule adsorbed on surface, L^2 (molecule) $^{-1}$
α_B	dimensionless statistical constant in Ergun equation

α_{ck}	fraction of coke generated that deposits on wall
α_p	fraction of catalyst surface poisoned, coked, or deactivated in some manner
β	solids angle of repose
β_B	constant in Ergun equation
β_d	constant in deactivation equation
Γ_A	ratio of mass-transfer rate of A to total rate of transfer of all components
γ'	constant in deactivation equation
$\gamma_A, \gamma_B, \dots, \gamma_R, \gamma_S, \dots, \gamma^\ddagger$	activity coefficients for indicated components
γ_A^*, γ_B^*	activity coefficient for indicated components that includes v_m
δ	fractional loss of selectivity
δ_A	change in moles per mole of A reacted
δ_c	thickness of combustion wave, L
δ_f	film thickness, L
δ_p	fraction of total pore length occupied by a plug of liquid
δ_v	fractional change in volume upon polymerization
δ_X	experimental error in conversion
ε	void fraction of a bed of catalyst
ε_b	fraction of fluidized bed occupied by bubbles
ε_{ch}	void fraction at choke
ε_l	liquid fraction of system volume below interface
ε_{mf}	void fraction at minimum fluidization velocity
ε_p	particle void fraction
ε_r	roughness of pipe
ε_w	screen porosity or void fraction
ζ_j	stoichiometric coefficient for species j relative to A, moles of j /mole of A in stoichiometric relation
η	effectiveness factor
η_I	inherent viscosity, $\ln(\eta_r)g^{-1}(100\text{ ml})$
η_O	effectiveness factor including bulk transport resistances
η_r	relative viscosity, polymer solution viscosity/solvent viscosity
$[\eta]_T$	intrinsic viscosity, dl./g
θ	angle

θ_a	fraction of surface covered at equilibrium adsorption
θ_s	fraction of sites available at any time
κ	transmission coefficient (see p. 17 ¹)
κ^∞	heat capacity ratio, c_p/c_r
κ_f	flow parameter (see Fig. 14.10 and Eq. 14.29)
Λ_t	fraction of fluid remaining longer than time t
λ	thermal conductivity, $HL^{-1}t^{-1}T^{-1}$
λ_a	axial thermal conductivity of catalyst bed, $HL^{-1}t^{-1}T^{-1}$
λ_{ck}	thermal conductivity of coke, $HL^{-1}t^{-1}T^{-1}$
$\lambda_e, \lambda_{ea}, \lambda_{ew}$	effective thermal conductivity general, of an aggregate of particles, and of an aggregate next to wall, $HL^{-1}t^{-1}T^{-1}$
λ_f	thermal conductivity of fluid, $HL^{-1}t^{-1}T^{-1}$
λ_g	gas conductivity, $HL^{-1}t^{-1}T^{-1}$
λ_l	effective thermal conductivity of catalyst particle, $HL^{-1}t^{-1}T^{-1}$
λ_r	effective radial thermal conductivity in operating catalyst bed, $HL^{-1}t^{-1}T^{-1}$
λ_r^f	fluid contribution to effective radial thermal conductivity, $HL^{-1}t^{-1}T^{-1}$
λ_r^s	solid contribution to effective radial thermal conductivity, $HL^{-1}t^{-1}T^{-1}$
λ_w	thermal conductivity of wall, $HL^{-1}t^{-1}T^{-1}$
μ	viscosity, $ML^{-1}t^{-1}$
μ_b	viscosity of bulk fluid, $ML^{-1}t^{-1}$
μ_{cr}	critical viscosity, $ML^{-1}t^{-1}$
μ_f	fluid viscosity, $ML^{-1}t^{-1}$
μ_g	viscosity of gas, $ML^{-1}t^{-1}$
μ_L	viscosity of liquid, $ML^{-1}t^{-1}$
μ_m	viscosity of mixture, $ML^{-1}t^{-1}$
μ_{mi}	viscosity, micropoise
μ_r	reduced viscosity, μ/μ_c
μ_w	viscosity at wall, $ML^{-1}t^{-1}$
ν	kinematic viscosity, L^2t^{-1}
$\nu_A, \nu_B, \nu_j, \dots, \nu_R, \nu_S, \dots, \nu^\dagger$	fugacity coefficients for indicated components
$\bar{\zeta}$	instantaneous number average degree of polymerization
ρ_b	bulk density, ML^{-3}
ρ_{ck}	density of coke, ML^{-3}
ρ_F	molar density of feed, (moles) L^{-3}

ρ_f	fluid density, ML^{-3}
ρ_g	gas or vapor density, ML^{-3}
ρ_L	density of liquid, ML^{-3}
ρ_p	particle density, ML^{-3}
ρ_{pr}	polymer density, ML^{-3}
ρ_s	solid density (excludes pore volume), ML^{-3}
σ	surface tension, Mt^{-2} or dynes/cm
σ_{AB}	distance between two molecules at collision when considered as rigid spheres, L
σ_c	critical surface tension, Mt^{-2}
σ_e	$\sigma_{AB}P^{\frac{1}{3}}$, related to collision cross section, L
τ	mean residence time for constant density flow, equivalent to holding time (reactor volume divided by volumetric flow rate) in plug flow and CSTR (backmixed reactor), t
Υ	tortuosity factor
Φ_s	effectiveness factor modulus in terms of observables (see Eq. 3.23)
ϕ_d	drop diffusion modulus (see Eq. 15.3)
ϕ_f, ϕ_q	correction constants in rate equations for gaseous and liquid reaction systems, respectively (see p. 37 ¹)
ϕ_L	Thiele modulus for flat slab (see p. 134 ¹)
ϕ_s	Thiele effectiveness factor modulus for spherical particle (see Eq. 3.14, 121 ¹)
ϕ_{sp}	sphericity factor (see Eqs. 11.17 and 13.2)
ψ	instantaneous activity, actual rate/rate at zero time or at start up
ω_A	$\delta_A y_{A_0}$
ω_e	(equivalent length of pipe)/(actual length)
ω_i	dispersed phase mixing frequency or interaction rate, volume mixed/(time)(volume of dispersed phase)

Frequently used subscripts:

e	effluent or product condition
f	fluid
i	value at interface; also any free radical
j	any component; also used to refer to jacket
<i>LM</i>	logarithmic mean
0	initial or feed condition
s	refers to surface of particle unless noted otherwise

Frequently used superscripts:

- f fluid
- ° standard state unless otherwise defined
- final discharge or product value
- s refers to surface of particle unless noted otherwise
- ‡ activated state
- * value at chemical equilibrium unless noted otherwise