

## A. EQUATION TABLES

- Table A-1 First law of thermodynamics for flow systems and the energy balance equations
- Table A-2 Basic thermodynamic relationships
- Table A-3 Ideal gas processes
- Table A-4 Equations of state of a real gas
- Table A-5 Types of liquid-gas (vapor) equilibria
- Table A-6 List of the more important equations describing the relation between the activity coefficients and solution composition for binary solutions
- Table A-7 List of the more important equations describing the relation between the activity coefficients and solution composition for binary solutions
- Table A-8 List of the more important equations describing the relation between the activity coefficients and solution composition for ternary solutions
- Table A-9 List of the more important equations describing the relation between the activity coefficients and solution composition for multicomponent solutions
- Table A-10 Equations of continuity
- Table A-11 Equations of motion
- Table A-12 Equations for free settling
- Table A-13 Energy equations for fluids with constant values of  $\rho$ ,  $\mu$ , and  $\lambda$
- Table A-14 Forms of energy equation
- Table A-15 Equations of continuity for a component of a mixture
- Table A-16 Forms of mass transfer equation
- Table A-17 Equations for steady-state diffusion
- Table A-18 Relationships between the mass transfer coefficients
- Table A-19 List of equations defining the Reynolds number for different flow types
- Table A-20 Some correlations to calculate the heat transfer coefficients
- Table A-21 Some correlations to calculate the mass transfer coefficients
- Table A-22 List of dimensionless parameters for heat and mass transfer
- Table A-23 Cases of mass transfer with an irreversible first order homogeneous chemical reaction (film model)
- Table A-24 Cases of mass transfer with an irreversible second order homogeneous chemical reaction (film model)
- Table A-25 Selected dimensionless numbers

Table A-1. First law of thermodynamics for flow systems and the energy balance equations

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1. General equation

$$\int_A (E + pV)(vn) dA + \frac{d}{dt} \int_v E \rho dv = \dot{q} + \dot{l}$$

$$E = U + gz + \frac{v^2}{2} \quad (\text{for 1 kg of fluid}); \quad e = Em; \quad \dot{q} = \frac{\delta q}{dt}; \quad \dot{l} = \frac{\delta l}{dt}$$

2. For multiple homogeneous streams

$$\sum_i \left[ \left( H + gz + \frac{v^2}{2} \right)_2 \dot{m}_2 \right]_t - \sum_i \left[ \left( H + gz + \frac{v^2}{2} \right)_1 \dot{m}_1 \right]_t + \frac{de}{dt} = \dot{q} + \dot{l}$$

3. For a finite process

$$\int_0^t \left[ \int_A (E + pV)(vn) dA \right] dt + \int_0^t \left( \frac{d}{dt} \int_v E \rho dv \right) dt = q + l$$

4. For an unsteady-state flow

$$\Delta u_{\text{syst.}} = \left( \sum_i h_i \right)_1 - \left( \sum_i h_i \right)_2 + q + l$$

$$h_i = H_i m_i; \quad \Delta z = 0; \quad \frac{\Delta v^2}{2} = 0$$

5. For steady state flow (homogeneous streams)

$$\sum_i \left[ \left( H + gz + \frac{v^2}{2} \right)_2 \dot{m}_2 \right] - \sum_i \left[ \left( H + gz + \frac{v^2}{2} \right)_1 \dot{m}_1 \right] = \dot{q} + \dot{l}$$

6. For a single stream, with respect to 1 kg of fluid (accounting for velocity profile)

$$\left( H + gz + \frac{v^2}{2\alpha} \right)_2 - \left( H + gz + \frac{v^2}{2\alpha} \right)_1 = Q + L_t$$

$$Q = \frac{\dot{q}}{m}; \quad L_t = \frac{\dot{l}_t}{m}; \quad \alpha - \text{constant in expression for kinetic energy of fluid}$$

7. Mechanical energy balance accounted for the work lost

$$\int_1^2 \frac{dp}{\rho} + g(z_2 - z_1) + \frac{v_2^2}{2\alpha_2} - \frac{v_1^2}{2\alpha_1} - L_t + L_s = 0$$


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Table A-2. Basic thermodynamic relationships

## 1. Maxwell equations

$$\left(\frac{\partial T}{\partial V}\right)_s = -\left(\frac{\partial p}{\partial S}\right)_v \quad \left(\frac{\partial T}{\partial p}\right)_s = \left(\frac{\partial V}{\partial S}\right)_p \quad \left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial p}{\partial T}\right)_v \quad \left(\frac{\partial S}{\partial p}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_v$$

## 2. Some important relationships

$$\begin{array}{lll} \left(\frac{\partial U}{\partial S}\right)_v = \left(\frac{\partial H}{\partial S}\right)_p = T & \left(\frac{\partial U}{\partial T}\right)_v = T \left(\frac{\partial S}{\partial T}\right)_v & \left(\frac{\partial U}{\partial p}\right)_s = -p \left(\frac{\partial V}{\partial p}\right)_s \\ \left(\frac{\partial H}{\partial p}\right)_s = \left(\frac{\partial G}{\partial p}\right)_T = V & \left(\frac{\partial H}{\partial T}\right)_p = T \left(\frac{\partial S}{\partial T}\right)_p & \left(\frac{\partial H}{\partial V}\right)_s = V \left(\frac{\partial p}{\partial V}\right)_s \\ \left(\frac{\partial F}{\partial V}\right)_T = \left(\frac{\partial U}{\partial V}\right)_s = -p & \left(\frac{\partial F}{\partial p}\right)_T = -p \left(\frac{\partial V}{\partial p}\right)_T & \left(\frac{\partial F}{\partial S}\right)_v = -S \left(\frac{\partial T}{\partial S}\right)_v \\ \left(\frac{\partial G}{\partial T}\right)_p = \left(\frac{\partial F}{\partial T}\right)_v = -S & \left(\frac{\partial G}{\partial V}\right)_T = V \left(\frac{\partial p}{\partial V}\right)_T & \left(\frac{\partial G}{\partial S}\right)_p = -S \left(\frac{\partial T}{\partial S}\right)_p \\ \left(\frac{\partial U}{\partial V}\right)_T = T \left(\frac{\partial p}{\partial T}\right)_v - p & \left(\frac{\partial H}{\partial p}\right)_T = V - T \left(\frac{\partial V}{\partial T}\right)_p & \left(\frac{\partial(\Delta G/T)}{\partial T}\right)_p = -\frac{\Delta H}{T^2} \end{array}$$

## 3. Relationships referring to heat capacities

$$\begin{array}{ll} \frac{C_p}{T} = \left(\frac{\partial V}{\partial T}\right)_p \left(\frac{\partial p}{\partial T}\right)_s = \left(\frac{\partial S}{\partial T}\right)_p & \frac{C_v}{T} = \left(\frac{\partial p}{\partial T}\right)_v \left(\frac{\partial V}{\partial T}\right)_s = \left(\frac{\partial S}{\partial T}\right)_v \\ C_p - C_v = -T \left(\frac{\partial p}{\partial T}\right)_v^2 \left(\frac{\partial V}{\partial p}\right)_T = -T \left(\frac{\partial V}{\partial T}\right)_p^2 \left(\frac{\partial p}{\partial V}\right)_T & \\ C_p - C_v = \left[ \left(\frac{\partial U}{\partial V}\right)_T + p \right] \left(\frac{\partial V}{\partial T}\right)_p & \frac{C_p}{C_v} = -\left(\frac{\partial V}{\partial T}\right)_p \left(\frac{\partial T}{\partial p}\right)_v \left(\frac{\partial p}{\partial V}\right)_s \\ \left(\frac{\partial C_p}{\partial p}\right)_T = -T \left(\frac{\partial^2 V}{\partial T^2}\right)_p & \left(\frac{\partial C_p}{\partial V}\right)_T = -T \left(\frac{\partial p}{\partial V}\right)_T \left(\frac{\partial^2 V}{\partial T^2}\right)_p \\ \left(\frac{\partial C_v}{\partial V}\right)_T = -T \left(\frac{\partial^2 p}{\partial T^2}\right)_v & \left(\frac{\partial C_v}{\partial p}\right)_T = -T \left(\frac{\partial V}{\partial p}\right)_T \left(\frac{\partial^2 p}{\partial T^2}\right)_v \end{array}$$

Table A-3. Ideal gas processes

Process type	Process equation	Relation between parameters of state	Work in the process	Heat in the process	Change of internal energy	Change of enthalpy	Heat capacity	Polytropic exponent
Isochoric	$V = \text{const}$	$\frac{P}{T} = \text{const}$	$L = 0$	$Q = C_v(T_2 - T_1)$	$\Delta U = C_v(T_2 - T_1)$	$\Delta H = C_p(T_2 - T_1)$	$C_v = \frac{R}{\kappa - 1}$	$k = \pm\infty$
Isohodic	$P = \text{const}$	$\frac{V}{T} = \text{const}$	$L = P(V_2 - V_1)$	$Q = C_p(T_2 - T_1)$	$\Delta U = C_v(T_2 - T_1)$	$\Delta H = \frac{Q}{\kappa - 1} = \frac{\kappa R}{\kappa - 1}$	$C_p = \frac{\kappa R}{\kappa - 1}$	$k = 0$
Isothermic	$T = \text{const}$	$PV = \text{const}$	$L = RT \ln \frac{V_1}{V_2} = RT \ln \frac{P_2}{P_1}$	$Q = -L$	$\Delta U = 0$	$\Delta H = 0$	$+ \infty, dV > 0$	$k = 1$
Adiabatic	$dQ = 0$	$PV^\kappa = \text{const}$	$L = \Delta U = C_v(T_2 - T_1) = \frac{1}{\kappa - 1}(PV_2 - PV_1)$	$Q = 0$	$\Delta U = L = C_v(T_2 - T_1)$	$\Delta H = \kappa L = C_p(T_2 - T_1)$	$C_a = 0$	$k = \kappa = \frac{C_p}{C_v}$
Polytropic	$C = \text{const}$	$\frac{P}{T^{1+\frac{1}{\kappa}}} = \text{const}$	$L = \frac{1}{\kappa - 1} \left[ \frac{P_2}{P_1} \right]^{\frac{\kappa-1}{\kappa}} - 1 = \frac{RT_1}{\kappa - 1} \left[ \frac{P_2}{P_1} \right]^{\frac{\kappa-1}{\kappa}} - 1 = \frac{PV_1}{\kappa - 1} \left[ \left( \frac{V_2}{V_1} \right)^{1-\kappa} - 1 \right]$	$Q = C(T_2 - T_1)$	$\Delta U = C_v(T_2 - T_1)$	$\Delta H = C_p(T_2 - T_1)$	$C = \frac{R(k - \kappa)}{(\kappa - 1)(k - 1)}$	$k = \frac{C - C_p}{C - C_v}$

**330 EQUATION TABLES**

Table A-4. Equations of state of a real gas

## 1. Gas constant

$$R = 8.31439 \text{ J/(K} \cdot \text{mol)}$$

$$R = 0.0820544 \text{ dm}^3 \cdot \text{atm/(K} \cdot \text{mol)}$$

$$R = 198719 \text{ cal/(K} \cdot \text{mol)}$$

## 2. General equation

$$pV = zRT$$

## 3. The virial equation

$$pV = A + Bp + Cp^2 + Dp^3 + \dots$$

$$B = V - \frac{A}{p} = V - \frac{RT}{p} = V - V^* = (z - 1) \frac{RT}{p} \quad \text{for } C, D, \dots = 0$$

## 4. The Van der Waals equation

$$\left( p + \frac{a}{V^2} \right) (V - b) = RT; \quad \left( p_c + \frac{3}{V_c^2} \right) (3V_c - 1) = 8T,$$

$$T_c = \frac{8a}{27bR}; \quad p_c = \frac{a}{27b^2}; \quad V_c = 3b$$

$$\text{for mixtures: } a_m^{v_2} = x_1 a_1^{v_2} + x_2 a_2^{v_2}; \quad b_m = x_1 b_1 + x_2 b_2$$

## 5. The Berthelot equation

$$\left( p + \frac{a'}{TV^2} \right) (V - b') = RT$$

## 6. The Beattie-Bridgeman equation

$$pV^2 = RT \left[ V + B_0 \left( 1 - \frac{b}{V} \right) \left[ 1 - \frac{c}{VT^3} \right] - A_0 \left( 1 - \frac{a}{V} \right) \right]$$

$$\text{constants are recalculated by: } A'_0 = A_0' \left( \frac{T_c}{T'} \right)^2 \left( \frac{p'_c}{p_c} \right)$$

Table A-4 (continued)

$$B_0, a, b, \alpha = a' \left( \frac{T_c}{T'_c} \right) \left( \frac{p'_c}{p_c} \right); \quad c = c' \left( \frac{T_c}{T'_c} \right)^4 \left( \frac{p'_c}{p_c} \right)$$

$$\text{for mixtures: } A_{0,m}^{1/2} = \sum x_i A_{0i}^{1/2}; \quad B_0, a, b, c, \alpha_m = \sum x_i \alpha_i$$

## 7. The Benedict-Webb-Rubin equation

$$p_r = \frac{T_r}{\Phi} + \frac{B'_0 T_r - A'_0 - \frac{C'_0}{T_r^2}}{\Phi^2} + \frac{b' T_r - a'}{\Phi^3} + \frac{a' \alpha'}{\Phi^6} + \frac{c'}{\Phi^3 T_r^2} \left( 1 + \frac{\gamma'}{\Phi^2} \right) e^{-\frac{T_r}{\Phi^2}}; \quad \Phi = \frac{V p_c}{R T_c}$$

$$A'_0 = 0.31315$$

$$a' = 0.059748$$

$$\alpha' = 0.0016081$$

$$B'_0 = 0.13464$$

$$b' = 0.043070$$

$$\gamma' = 0.042113$$

$$C'_0 = 0.16920$$

$$c' = 0.059416$$

## 8. Cubic equations of state

## (a) Redlich-Kwong equation

$$p = \frac{RT}{V - b} - \frac{a}{\sqrt{TV(V+b)}}; \quad a = \frac{0.42748 R^2 T_c^{2.5}}{p_c}; \quad b = \frac{0.08664 RT_c}{p_c}$$

$$z^3 - z^2 + (A - B - B^2)z - AB = 0; \quad A = \frac{ap}{R^2 T^{2.5}} = \frac{0.42748 p_r}{T_r}; \quad B = \frac{bp}{RT} = \frac{0.08664 p_r}{T_r}$$

for mixtures:

$$\alpha_m = \sum \sum x_i x_j a_{ij}; \quad b_m = \sum x_i b_i; \quad A_m = \sum \sum x_i x_j A_{ij}; \quad B_m = \sum x_i B_i$$

$$\text{cross-parameters: } a_{ij} = \sqrt{a_i a_j}; \quad A_{ij} = \sqrt{A_i A_j}$$

## (b) Soave equation

$$p = \frac{RT}{V - b} - \frac{\alpha \alpha}{V(V+b)}; \quad a = \frac{0.42748 R^2 T_c^2}{p_c}; \quad b = \frac{0.08664 RT_c}{p_c}$$

$$\alpha = [1 + s(1 - T_r^{1/2})]^2; \quad s = 0.48 + 1.57\omega - 0.176\omega^2;$$

where  $\omega$  is the Pitzer parameter,

$$\omega = -\log_{10} p_r (\text{at } T_r = 0.7) - 1.000$$

## 332 EQUATION TABLES

Table A-4 (continued)

$$z^3 - z^2 + (A - B - B^2)z - AB = 0; \quad A = \frac{\alpha a p}{R^2 T^2} = \frac{0.42748 \alpha p_r}{T_r}; \quad B = \frac{b p}{RT} = \frac{0.08664 p_r}{T_r}$$

for mixtures:

$$(\alpha a)_m = \sum \sum x_i x_j (\alpha a)_i; \quad b_m = \sum x_i b_i; \quad A_m = \sum \sum x_i x_j A_i; \quad B_m = \sum x_i B_i$$

cross-parameters:

$$(\alpha a)_i = (1 - k_{ij}) \sqrt{(\alpha a)_j (\alpha a)_j}$$

Values of the cross-parameters  $k_{ij}$  for a number of substances are listed in.<sup>1</sup>

(c) Peng-Robinson equation

$$p = \frac{RT}{V - b} - \frac{\alpha \alpha}{V^2 + 2bV - b^2}; \quad a = \frac{0.45724 R^2 T_c^2}{p_c}; \quad b = \frac{0.077804 RT_c}{p_c}$$

$$\alpha = [1 + s(1 - T_r^{1/2})]^2; \quad s = 0.37464 + 1.5226\omega - 0.26992\omega^2;$$

where  $\omega$  is the Pitzer parameter;

$$\omega = -\log_{10} p_r \text{ (at } T_r = 0.7) - 1.000$$

$$z^3 - (1 - B)z^2 + (A - 3B^2 - 2B)z - (AB - B^2 - B^3) = 0$$

$$A = \frac{\alpha a p}{R^2 T^2} = \frac{0.45724 \alpha p_r}{T_r}; \quad B = \frac{b p}{RT} = \frac{0.077804 p_r}{T_r}$$

for mixtures:

$$(\alpha a)_m = \sum \sum x_i x_j (\alpha a)_i; \quad b_m = \sum x_i b_i; \quad A_m = \sum \sum x_i x_j A_i; \quad B_m = \sum x_i B_i$$

cross-parameters:

$$(\alpha a)_i = (1 - k_{ij}) \sqrt{(\alpha a)_j (\alpha a)_j}; \quad A_i = (1 - k_{ii}) \sqrt{A_i A_i}; \quad k_{ii} = 0$$

Values of the cross-parameters  $k_{ij}$  for a number of substances are listed in.<sup>1</sup>

### 9. Lee-Kesler equation of state

$$z = \frac{\Phi_r p_r}{T_r} = 1 + \frac{B}{\Phi_r} + \frac{C}{\Phi_r^2} + \frac{D}{\Phi_r^3} + \frac{c_4}{T_r^3 \Phi_r^2} \left( \beta + \frac{\gamma}{\Phi_r^2} \right) \exp \left( -\frac{\gamma}{\Phi_r^2} \right)$$

$$B = b_1 - \frac{b_2}{T_r} - \frac{b_3}{T_r^2} - \frac{b_4}{T_r^3}; \quad C = c_1 - \frac{c_2}{T_r} + \frac{c_3}{T_r^3}; \quad D = d_1 + \frac{d_2}{T_r}$$

$$\Phi_r = \frac{V p_c}{R T_c} = \frac{z T_r}{p_r}; \quad z = z^{(0)} + \frac{\omega}{\omega^{(r)}} (z^{(r)} - z^{(0)}); \quad \omega^{(r)} = 0.3978$$

Table A-4 (continued)

Constant	Simple fluids	Reference fluids
$b_1$	0.11811193	0.2026579
$b_2$	0.265728	0.331511
$b_3$	0.154790	0.027655
$b_4$	0.030323	0.203488
$c_1$	0.0236744	0.0313385
$c_2$	0.0186984	0.0503618
$c_3$	0.0	0.016901
$c_4$	0.042724	0.041577
$d_1 \cdot 10^4$	0.155488	0.48736
$d_2 \cdot 10^4$	0.623689	0.0740336
$\beta$	0.65392	1.226
$\gamma$	0.060167	0.03754

for mixtures, pseudocritical parameters:

$$V_{cl} = \frac{z_{cl} RT_{cl}}{p_{cl}}; \quad z_{cl} = 0.2905 - 0.085\omega_i;$$

$$V_c = \frac{1}{8} \sum_i \sum_j x_i x_j (V_{cl}^{1/3} + V_{cj}^{1/3})^3; \quad \omega = \sum_i x_i \omega_i$$

$$T_c = \frac{1}{8V_c} \sum_i \sum_j x_i x_j (V_{cl}^{1/3} + V_{cj}^{1/3})^3 \sqrt{T_{cl} T_{cj}};$$

$$p_c = \frac{z_c RT_c}{V_c} = \frac{(0.02905 - 0.085\omega)RT_c}{V_c}$$

<sup>1</sup> Walas S. M., *Phase Equilibria in Chemical Engineering*, Butterworth Publishers, Stoneham, MAS, 1985.

Table A-5. Types of liquid-gas (vapor) equilibria

Type	System type			Distillation equilibrium equation	$K_i$	Absorption equilibrium equation	Notes
Gas phase	Gas solution	Gas	Liquid solution				
I	i	i	i	$y_i P = x_i P_i \exp \frac{V_i(P - P_i)}{RT} = x_i P_i \Psi$	$\frac{P_i}{P}$	$P_i = E_i x_i = P_i'' x_i$	$P < 0.2 \text{ MPa}$ $\gamma_i = 1, \Psi \approx 1$
II	i	i	r	$y_i P = \gamma_i x_i P_i \Psi$	$\frac{\gamma_i P_i}{P}$	$P_i = E_i x_i = P_i'' \gamma_i x_i$	$P < 0.2 \text{ MPa}$ $\gamma_i \neq 1, \Psi \approx 1$
III	r	i	i	$y_i (a_{\mu})_p = x_i (a_{\mu})_p \Psi$	$\frac{(a_{\mu})_p \Psi}{(a_{\mu})_p}$	$y_i (a_{\mu})_p = E_p x_i$	$P < 2-3 \text{ MPa}$ $(P < 0.5 P_i), \gamma_i = 1$
IV	r	i	r	$y_i (a_{\mu})_p = \gamma_i x_i (a_{\mu})_p \Psi$	$\frac{\gamma_i (a_{\mu})_p \Psi}{(a_{\mu})_p}$	$y_i (a_{\mu})_p = E_p x_i$	$P < 2-3 \text{ MPa}$ $(P < 0.5 P_i), \gamma_i \neq 1$
V	r	r	r	$(a_{\mu})'' = \gamma_i x_i (a_{\mu})_p \Psi$	-	$(a_{\mu})'' = E_p x_i$	-
i - ideal, r - real				$\Psi = \exp \frac{V_i(P - P_i)}{RT}$	$K_i = \frac{y_i}{x_i}$		

Table A-6. List of the more important equations describing the relation between the activity coefficients and solution composition for binary solutions

Type and order of equation	Simplifications	$z$	$\log \gamma_1$	$\log \gamma_2$
Wohl 4	$\frac{1}{1 + \left(\frac{q_2}{q_1}\right)\left(\frac{1-x}{x}\right)}$	$(1-z)^2 \left[ A + 2z \left( B \frac{q_1}{q_2} - A - D \right) + 3z^2 D \right]$	$z^2 \left[ B + 2(1-z) \left( A \frac{q_2}{q_1} - B - D \frac{q_2}{q_1} \right) + 3(1-z)^2 D \frac{q_2}{q_1} \right]$	
		$(1-z)^2 \left[ A + 2z \left( B \frac{q_1}{q_2} - A \right) \right]$	$z^2 \left[ B + 2(1-z) \left( A \frac{q_2}{q_1} - B \right) \right]$	
Scatchard 4	$\frac{q_2}{q_1} = \frac{V_2}{V_1}$	$(1-z)^2 \left[ A + 2z \left( B \frac{V_1}{V_2} - A - D \right) + 3z^2 D \right]$	$z^2 \left[ B + 2(1-z) \left( A \frac{V_2}{V_1} - B - D \frac{V_2}{V_1} \right) + 3(1-z)^2 D \frac{V_2}{V_1} \right]$	
		$(1-z)^2 \left[ A + 2z \left( B \frac{V_1}{V_2} - A \right) \right]$	$z^2 \left[ B + 2(1-z) \left( A \frac{V_2}{V_1} - B \right) \right]$	
van Laar 4	$\frac{q_2}{q_1} = \frac{B}{A}$	$(1-z)^2 \left[ A + z(3z - 2D) \right]$	$z^2 \left[ B + (1-z)(1-3z)(DB/A) \right]$	
		$(1-z)^2 A = \frac{A}{\left[ 1 + \frac{A}{B} \left( \frac{x}{1-x} \right) \right]^2}$	$z^2 B = \frac{B}{\left[ 1 + \frac{B}{A} \left( \frac{1-x}{x} \right) \right]^2}$	
van Laar-Null 4	$\frac{q_2}{q_1} = \frac{ B }{ A }$	$(1-z)^2 \left[ A + 2z \left( B \frac{ A }{ B } - A \right) + z(z-2)D \right]$	$z^2 \left[ B + 2(1-z) \left( A \frac{ B }{ A } - B \right) + (1-z)(1-3z)D \frac{ B }{ A } \right]$	
		$(1-z)^2 A \left[ 1 + 2z \left( \frac{ A B}{ A  B } - 1 \right) \right]$	$z^2 B \left[ 1 + 2(1-z) \left( \frac{ A  B }{ A  B } - 1 \right) \right]$	

Table A-6 (continued)

Margules	4	$\frac{q_1}{q_2} = 1$	$x$	$(1-x)^2 [A + 2x(B-A-D) + 3x^2D]$	$x^2 [B + 2(1-x)(A-B-D) + 3(1-x)^2D]$
	3			$(1-x)^2 [A + 2x(B-A)]$	$x^2 [B + 2(1-x)(A-B)]$
Symmetric	4	$\frac{q_1}{q_2} = 1$	$x$	$(1-x)^2 [A + x(3x-2)D]$	$x^2 [A + (1-x)(1-3x)D]$
	$3 \equiv 2$	$A = B$		$(1-x)^2 A$	$x^2 A$
<hr/>					
$A = q_1(2q_{12} + 3q_{112} + 4q_{122}), \quad B = q_1(2q_{12} + 3q_{12} + 4q_{112}), \quad D = q_1(4q_{112} + 4q_{122} - 6q_{112})$					
<hr/>					

Note: In multiplying  $A$ ,  $B$ , and  $D$  by 2.303, equations adjusted to get  $\ln \gamma_i$  can be obtained.

<sup>1</sup> After Hála E., Pick J., Fried V., and Vilim O., *Vapour-Liquid Equilibrium*, 2nd ed., Pergamon Press, London, 1967 (by permission); Hála E., *Chemické listy*, 71, 338, 1977 (by permission).

Table A-7. List of the more important equations describing the relation between the activity coefficients and solution composition for binary solutions<sup>1</sup>

Type and order of equation	$\ln \gamma_1$	$\ln \gamma_2$
Redlich-Kister 4	$x_2^2 [b_{12} + (3x_1 - x_2)c_{12} + (x_1 - x_2)(5x_1 - x_2)d_{12}]$	$x_1^2 [b_{12} - (3x_2 - x_1)e_{12} + (x_2 - x_1)(5x_2 - x_1)f_{12}]$
	$x_2^2 [b_{12} + (3x_1 - x_2)c_{12}]$	$x_1^2 [b_{12} - (3x_2 - x_1)e_{12}]$
Wilson	$1 - \ln(x_1 + x_2 A_{12}) - \frac{x_1}{x_1 + x_2 A_{12}} - \frac{x_2 A_{21}}{x_2 + x_1 A_{21}}$	$1 - \ln(x_2 + x_1 A_{21}) - \frac{x_2}{x_2 + x_1 A_{21}} - \frac{x_1 A_{12}}{x_1 + x_2 A_{12}}$
Black	$A_{12} \left( \frac{x_2 A_{21}}{x_1 A_{12} + x_2 A_{21}} \right)^2 + x_1^2 (2x_2 - 1) (6x_2 - 5) C$	$A_{12} \left( \frac{x_1 A_{12}}{x_1 A_{12} + x_2 A_{21}} \right)^2 + x_1^2 (2x_1 - 1) (6x_1 - 5) C$
Fariss	$\frac{A_{12}}{1 + x_1 x_2 B} \left( \frac{x_2 A_{21}}{x_1 A_{12} + x_2 A_{21}} \right)^2 \left[ 1 + \frac{x_1 (2x_1 - 1) B \left( \frac{A_{12}}{A_{21}} x_1 + x_2 \right)}{1 + x_1 x_2 B} \right]$	$\frac{A_{12}}{1 + x_1 x_2 B} \left( \frac{x_1 A_{12}}{x_2 A_{12} + x_1 A_{21}} \right)^2 \left[ 1 + \frac{x_2 (2x_2 - 1) B \left( \frac{A_{21}}{A_{12}} x_2 + x_1 \right)}{1 + x_1 x_2 B} \right]$
Renon-Prausnitz (NRTL)	$x_2^2 \left[ A_{12} \left( \frac{B_{21}}{x_1 + x_2 B_{21}} \right)^2 + \frac{A_{12} B_{21}}{(x_2 + x_1 B_{21})^2} \right]$	$x_1^2 \left[ A_{12} \left( \frac{B_{12}}{x_2 + x_1 B_{12}} \right)^2 + \frac{A_{12} B_{12}}{(x_1 + x_2 B_{12})^2} \right]$

Note: The constants  $A_{ij}$  and  $B_{ij}$  have different values in different equations.

<sup>1</sup> Hála E., *Chemicke listy*, 71, 338, 1977 (by permission).

**Table A-8.** List of the more important equations describing the relation between the activity coefficients and solution composition for ternary solutions<sup>1</sup>

Type and order of equation	Simplification	$z$	$\log \gamma_1$
Wohl 4	-	$z_1 = \frac{x_1}{x_1 + x_2 \frac{q_2}{q_1} + x_3 \frac{q_3}{q_1}}$ $z_2 = \frac{x_2 \frac{q_2}{q_1}}{x_1 + x_2 \frac{q_2}{q_1} + x_3 \frac{q_3}{q_1}}$ $z_3 = \frac{x_3 \frac{q_3}{q_1}}{x_1 + x_2 \frac{q_2}{q_1} + x_3 \frac{q_3}{q_1}}$	$z_1^2 \left[ A_{12} + 2z_1 \left( A_{21} \frac{q_1}{q_2} - A_{12} - D_{12} \right) + 3z_1^2 D_{12} \right] + z_2^2 \cdot$ $\cdot \left[ A_{13} + 2z_1 \left( A_{31} \frac{q_1}{q_3} - A_{13} - D_{13} \frac{q_1}{q_3} \right) + 3z_1^2 D_{13} \frac{q_1}{q_3} \right] +$ $+ z_2 z_3 \left[ A_{21} \frac{q_1}{q_2} + A_{13} - A_{32} \frac{q_1}{q_3} + 2z_1 \left( A_{31} \frac{q_1}{q_3} - A_{13} \right) + \right.$ $+ 2z_3 \left( A_{32} \frac{q_1}{q_3} - A_{23} \frac{q_1}{q_2} \right) + 3z_2 z_3 D_{23} \frac{q_1}{q_2} - C_1 z_1 \cdot$ $\cdot (2 - 3z_1) - C_2 z_1 (1 - 3z_1) \frac{q_1}{q_2} - C_3 z_3 (1 - 3z_1) \frac{q_1}{q_3} \Big]$
	3		$z_2^2 \left[ A_{12} + 2z_1 \left( A_{21} \frac{q_1}{q_2} - A_{12} \right) \right] +$ $+ z_3^2 \left[ A_{13} + 2z_1 \left( A_{31} \frac{q_1}{q_3} - A_{13} \right) \right] +$ $+ z_2 z_3 \left[ A_{21} \frac{q_1}{q_2} + A_{13} - A_{32} \frac{q_1}{q_3} + 2z_1 \left( A_{31} \frac{q_1}{q_3} - A_{13} \right) + \right.$ $+ 2z_3 \left( A_{32} \frac{q_1}{q_3} - A_{23} \frac{q_1}{q_2} \right) - C (1 - 2z_1) \Big]$
Margules 4	$\frac{q_2}{q_1} = 1$ $\frac{q_3}{q_1} = 1$ $\frac{q_3}{q_2} = 1$	$z_1 = x_1$ $z_2 = x_2$ $z_3 = x_3$	$x_1^2 \left[ A_{12} + 2x_1 (A_{21} - A_{12} - D_{12}) + 3x_1^2 D_{12} \right] +$ $+ x_3^2 \left[ A_{13} + 2x_1 (A_{31} - A_{13} - D_{13}) + 3x_1^2 D_{13} \right] +$ $+ x_1 x_3 \left[ A_{21} + A_{13} - A_{32} + 2x_1 (A_{31} - A_{13}) + \right.$ $+ 2x_3 (A_{32} - A_{23}) + 3x_1 x_3 D_{23} - C_1 x_1 (2 - 3x_1) +$ $\left. - C_2 x_2 (1 - 3x_1) - C_3 x_3 (1 - 3x_1) \right]$
	3		$x_1^2 \left[ A_{12} + 2x_1 (A_{21} - A_{12}) \right] + x_3^2 \left[ A_{13} + 2x_1 (A_{31} - A_{13}) \right] + x_1 x_3 \left[ A_{21} + A_{13} - A_{32} + \right.$ $+ 2x_1 (A_{31} - A_{13}) + 2x_3 (A_{32} - A_{23}) - C (1 - 2x_1) \Big]$

Table A-8. (continued)

$\log \gamma_2$	$\log \gamma_3$
$z_1^2 \left[ A_{21} + 2z_2 \left( A_{12} \frac{q_2}{q_1} - A_{21} - D_{12} \frac{q_2}{q_1} \right) + 3z_2^2 D_{12} \frac{q_2}{q_1} \right] + z_1^2 \left[ A_{31} + 2z_3 \left( A_{13} \frac{q_3}{q_1} - A_{31} - D_{13} \frac{q_3}{q_1} \right) + 3z_3^2 D_{13} \frac{q_3}{q_1} \right] + z_2^2 \left[ A_{23} + 2z_2 \left( A_{23} \frac{q_2}{q_3} - A_{23} - D_{23} \frac{q_2}{q_3} \right) + 3z_2^2 D_{23} \frac{q_2}{q_3} \right] + z_1 z_3 \left[ A_{21} \frac{q_1}{q_3} + A_{21} - A_{13} \frac{q_1}{q_3} + 2z_2 \left( A_{12} \frac{q_2}{q_1} - A_{21} \frac{q_2}{q_1} \right) + 2z_1 \left( A_{13} \frac{q_1}{q_2} - A_{31} \frac{q_1}{q_2} \right) + 3z_1 z_3 D_{13} \frac{q_1}{q_3} - C_1 z_2 \cdot (2 - 3z_2) - C_3 z_3 \frac{q_1}{q_3} - C_1 z_1 (1 - 3z_2) \frac{q_2}{q_1} - C_1 z_1 (1 - 3z_2) \frac{q_2}{q_1} \right]$	$z_1^2 \left[ A_{31} + 2z_3 \left( A_{13} \frac{q_3}{q_1} - A_{31} - D_{13} \frac{q_3}{q_1} \right) + 3z_3^2 D_{13} \frac{q_3}{q_1} \right] + z_2^2 \left[ A_{32} + 2z_3 \left( A_{23} \frac{q_3}{q_2} - A_{32} - D_{23} \frac{q_3}{q_2} \right) + 3z_3^2 D_{23} \frac{q_3}{q_2} \right] + z_1 z_2 \left[ A_{13} \frac{q_3}{q_1} + A_{32} + A_{21} \frac{q_3}{q_2} + 2z_3 \left( A_{23} \frac{q_3}{q_2} - A_{32} \frac{q_3}{q_2} \right) + 2z_2 \left( A_{21} \frac{q_3}{q_2} - A_{12} \frac{q_3}{q_1} \right) - 3z_1 z_2 D_{12} \frac{q_3}{q_1} - C_3 z_3 \cdot (2 - 3z_3) - C_1 z_1 (1 - 3z_3) \frac{q_3}{q_1} - C_2 z_2 (1 - 3z_3) \frac{q_3}{q_2} \right]$
$z_1^2 \left[ A_{21} + 2z_2 \left( A_{12} \frac{q_2}{q_1} - A_{21} \right) \right] + z_1^2 \left[ A_{23} + 2z_2 \left( A_{23} \frac{q_2}{q_3} - A_{23} \right) \right] + z_1 z_3 \left[ A_{32} \frac{q_1}{q_3} + A_{21} - A_{13} \frac{q_1}{q_3} + 2z_2 \left( A_{12} \frac{q_2}{q_1} - A_{21} \frac{q_2}{q_1} \right) + 2z_1 \left( A_{13} \frac{q_1}{q_2} - A_{31} \frac{q_1}{q_2} \right) - C (1 - 2z_2) \frac{q_2}{q_1} \right]$	$z_1^2 \left[ A_{31} + 2z_3 \left( A_{13} \frac{q_3}{q_1} - A_{31} \right) \right] + z_2^2 \left[ A_{32} + 2z_3 \left( A_{23} \frac{q_3}{q_2} - A_{32} \right) \right] + z_1 z_2 \left[ A_{13} \frac{q_3}{q_1} + A_{32} - A_{21} \frac{q_3}{q_2} + 2z_3 \left( A_{23} \frac{q_3}{q_2} - A_{32} \frac{q_3}{q_2} \right) + 2z_2 \left( A_{21} \frac{q_3}{q_2} - A_{12} \frac{q_3}{q_1} \right) - C (1 - 2z_3) \frac{q_3}{q_1} \right]$
$x_1^2 \left[ A_{21} + 2x_2 (A_{12} - A_{21} - D_{12}) + 3x_2^2 D_{12} \right] + x_1^2 \left[ A_{23} + 2x_2 (A_{23} - A_{21} - D_{23}) + 3x_2^2 D_{23} \right] + x_1 x_3 \left[ A_{21} + A_{21} - A_{13} + 2x_2 (A_{12} - A_{21}) + 2x_1 (A_{13} - A_{31}) + 3x_1 x_3 D_{13} - C_2 x_2 (2 - 3x_2) + -C_3 x_3 (1 - 3x_2) - C_1 x_1 (1 - 3x_2) \right]$	$x_1^2 \left[ A_{31} + 2x_3 (A_{13} - A_{31} - D_{13}) + 3x_3^2 D_{13} \right] + x_1^2 \left[ A_{32} + 2x_3 (A_{23} - A_{32} - D_{23}) + 3x_3^2 D_{23} \right] + x_1 x_2 \left[ A_{13} + A_{32} - A_{21} + 2x_3 (A_{23} - A_{32}) + 2x_2 (A_{21} - A_{12}) + 3x_1 x_2 D_{12} - C_3 x_3 (2 - 3x_3) + -C_1 x_1 (1 - 3x_3) - C_2 x_2 (1 - 3x_3) \right]$
$x_1^2 \left[ A_{21} + 2x_2 (A_{12} - A_{21}) \right] + x_3^2 \left[ A_{23} + 2x_2 (A_{23} - A_{21}) \right] + x_1 x_3 \left[ A_{21} + A_{21} - A_{13} + 2x_2 (A_{12} - A_{21}) + 2x_1 (A_{13} - A_{31}) - C (1 - 2x_2) \right]$	$x_1^2 \left[ A_{31} + 2x_3 (A_{13} - A_{31}) \right] + x_2^2 \left[ A_{32} + 2x_3 (A_{23} - A_{32}) \right] + x_1 x_2 \left[ A_{13} + A_{32} - A_{21} + 2x_3 (A_{23} - A_{32}) + 2x_2 (A_{21} - A_{12}) - C (1 - 2x_3) \right]$

Table A-8 (continued)

Type and order of equation	Simplification	$z$	$\log \gamma_1$
Symmetric 4	$\frac{q_2}{q_1} = 1$ $\frac{q_3}{q_1} = 1$ $\frac{q_3}{q_2} = 1$	$z_1 = x_1$ $z_2 = x_2$ $z_3 = x_3$	$x_1^2 [A_{12} + x_1(3x_1 - 2)D_{12}] + x_3^2 [A_{13} + x_1(3x_1 - 2)D_{13}] + x_2x_3 [A_{12} + A_{13} - A_{23} + 3x_2x_3 D_{23} - x_1(2 - 3x_1)C_1 + x_2(1 - 3x_1)C_2 - x_3(1 - 3x_1)C_3]$
3	$A_{21} = A_{12}$ $A_{31} = A_{13}$ $A_{32} = A_{23}$		$x_1^2 A_{12} + x_3^2 A_{13} + x_2x_3 [A_{12} + A_{13} - A_{23} + C(1 - 2x_1)]$
van Laar	3 2	$z_1 = \frac{x_1}{x_1 + x_2 \frac{A_{21}}{A_{12}} + x_3 \frac{A_{31}}{A_{13}}}$ $z_2 = \frac{x_2 \frac{A_{21}}{A_{12}}}{x_1 + x_2 \frac{A_{21}}{A_{12}} + x_3 \frac{A_{31}}{A_{13}}}$ $z_3 = \frac{x_3 \frac{A_{31}}{A_{13}}}{x_1 + x_2 \frac{A_{21}}{A_{12}} + x_3 \frac{A_{31}}{A_{13}}}$	$z_1^2 A_{12} + z_2^2 A_{13} + z_1 z_3 \left[ A_{12} + A_{13} - A_{23} \frac{A_{13}}{A_{31}} + C(1 - 2z_1) \right]$ $z_1^2 A_{12} + z_2^2 A_{13} + z_1 z_3 \left( A_{12} + A_{13} - A_{23} \frac{A_{13}}{A_{31}} \right) =$ $= \frac{1}{\left( x_1 + x_2 \frac{A_{21}}{A_{12}} + x_3 \frac{A_{31}}{A_{13}} \right)^2} \left[ x_1^2 A_{12} \left( \frac{A_{21}}{A_{12}} \right)^2 + x_3^2 \cdot A_{13} \left( \frac{A_{31}}{A_{13}} \right)^2 + x_2 x_3 \left( A_{12} + A_{13} - A_{23} \frac{A_{13}}{A_{31}} \right) \frac{A_{21} A_{31}}{A_{12} A_{13}} \right]$

Table A-8 (continued)

$\log \gamma_2$	$\log \gamma_3$
$x_1^2 [A_{12} + x_2 (3x_2 - 2)D_{12}] + x_3^2 [A_{23} +$ $+ x_2 (3x_2 - 2)D_{23}] + x_1 x_3 [A_{23} + A_{12} - A_{13} +$ $+ 3x_1 x_3 D_{13} - x_2 (2 - 3x_2)C_2 + x_3 (1 - 3x_2)C_3 +$ $- x_1 (1 - 3x_2)C_1]$	$x_1^2 [A_{13} + x_3 (3x_3 - 2)D_{13}] + x_2^2 [A_{23} +$ $+ x_3 (3x_3 - 2)D_{23}] + x_1 x_2 [A_{13} + A_{23} - A_{12} +$ $+ 3x_1 x_2 D_{12} - x_3 (2 - 3x_3)C_3 - x_1 (1 - 3x_3)C_1 +$ $- x_2 (1 - 3x_3)C_2]$
$x_1^2 A_{12} + x_3^2 A_{23} + x_1 x_3 [A_{23} + A_{12} - A_{13} +$ $- C(1 - 2x_2)]$	$x_1^2 A_{13} + x_2^2 A_{23} + x_1 x_2 [A_{13} + A_{23} - A_{12} +$ $- C(1 - 2x_3)]$
$z_1^2 A_{21} + z_3^2 A_{23} + z_1 z_3 \left[ A_{23} + A_{21} - A_{13} \frac{A_{21}}{A_{12}} + \right.$ $\left. - C(1 - 2z_2) \frac{A_{21}}{A_{12}} \right]$	$z_1^2 A_{31} + z_2^2 A_{32} + z_1 z_2 \left[ A_{31} + A_{32} - A_{21} \frac{A_{32}}{A_{23}} + \right.$ $\left. - C(1 - 2z_3) \frac{A_{31}}{A_{13}} \right]$
$z_1^2 A_{21} + z_3^2 A_{23} + z_1 z_3 \left( A_{23} + A_{21} - A_{13} \frac{A_{21}}{A_{12}} \right) =$ $= \frac{\left( \frac{A_{21}}{A_{12}} \right)^2}{\left( x_1 + x_2 \frac{A_{21}}{A_{12}} + x_3 \frac{A_{31}}{A_{13}} \right)^2} \left[ x_1^2 A_{21} \left( \frac{A_{12}}{A_{21}} \right)^2 + x_3^2 \cdot \right.$ $\left. \cdot A_{23} \left( \frac{A_{32}}{A_{23}} \right)^2 + x_1 x_3 \left( A_{23} + A_{21} - A_{13} \frac{A_{21}}{A_{12}} \right) \frac{A_{32} A_{12}}{A_{23} A_{21}} \right]$	$z_1^2 A_{31} + z_2^2 A_{32} + z_1 z_2 \left( A_{31} + A_{32} - A_{21} \frac{A_{32}}{A_{23}} \right) =$ $= \frac{\left( \frac{A_{31}}{A_{13}} \right)^2}{\left( x_1 + x_2 \frac{A_{21}}{A_{12}} + x_3 \frac{A_{31}}{A_{13}} \right)^2} \left[ x_1^2 A_{31} \left( \frac{A_{13}}{A_{31}} \right)^2 + x_2^2 \cdot \right.$ $\left. \cdot A_{32} \left( \frac{A_{23}}{A_{32}} \right)^2 + x_1 x_2 \left( A_{31} + A_{32} - A_{21} \frac{A_{32}}{A_{23}} \right) \frac{A_{13} A_{23}}{A_{31} A_{32}} \right]$

Note: In multiplying  $A$ ,  $C$ , and  $D$  by 2.303, equations adjusted to get  $\ln \gamma_i$  can be obtained.

<sup>1</sup> After Hála E., Pick J., Fried V., and Vilim O., *Vapour-Liquid Equilibrium*, 2nd ed., Pergamon Press, London, 1967 (by permission).

Table A.9. List of the more important equations describing the relation between the activity coefficients and solution composition for multicomponent solutions.

Type of equation	Assumptions	$\ln \gamma_i$	Notes
Chien-Null	-	$\frac{1}{2} \left[ \left( \sum_i x_i A_{ix} \right) \left( \sum_i x_i R_{ix} \right) + \sum_i x_i \left( \sum_i x_j V_{ix} \right) \left( \sum_i x_j S_{ix} \right) \right]$ $\cdot \left( \frac{A_v}{\sum_i x_i A_{ix}} + \frac{R_v}{\sum_i x_i R_{ix}} - \frac{S_v}{\sum_i x_i S_{ix}} - \frac{V_v}{\sum_i x_i V_{ix}} \right)$	$R_{ji} = \frac{A_{ji}}{A_{ii}}$ ; $A_{ii} = 0$ ; $\frac{A_u}{A_u} = 1$
van Laar	$V_{ji} = S_{ji} = \frac{A_{ji}}{A_{ii}}$	$\sum_k z_k A_{ik} - \frac{1}{2} \sum_i \sum_k z_k z_l A_{ik} \frac{A_{lr}}{A_{ii}}$	$z_r = \frac{x_r q_r}{\sum_k x_k q_k}$ ; $z_s = \frac{x_s q_s}{\sum_k x_k q_k}$ $q_i = \frac{A_{ii}}{A_{ii}}$ ; $\frac{A_{ij}}{A_{ii}} = \frac{A_{ik}}{A_{ii}} \frac{A_{kj}}{A_{jk}}$
Farris	$R_{ij} = 1$ ; $S_{ij} = \left  \frac{A_{ij}}{A_{ii}} \right $ ; $V_{ij} = V_{ji} = \frac{1}{2} \sum_i \sum_k Q_{in} + \frac{1}{2} \left[ \sum_i \frac{x_i (a_{ii} - Q_{in} B_{in})}{1 + x_i x_j B_{in}} + \frac{Q_{in} (A_{ii} - A_{ji})}{2 A_{ii} A_{ji}} \right] +$ $= \frac{1}{2} \left[ B_{ij} + 2 + \sqrt{(B_{ij} + 2)^2 - 4} \right] - \sum_i \sum_k x_i \left[ \frac{x_i (a_{ii} - Q_{in} B_{in})}{1 + x_i x_j B_{in}} + \frac{Q_{in} a_{in} (A_{ii} - A_{ji})}{2 A_{ii} A_{ji}} \right]$ $A_{ij} = \frac{2 V_{ij} (\ln \gamma_{ji}^*)}{V_{ij} \pm 1}$	$Q_{in} = \frac{x_i x_j q_{in}}{1 + x_i x_j B_{in}}$ $a_{in} = \frac{A_{in} (1 + x_i - x_j) + A_{ji} (1 + x_i - x_j)}{A_{in}}$ $A_{ji} = \ln \gamma_{ji}^*$ ; $A_{ji} = \ln \gamma_{ji}^*$ $A_{in} = A_{ji} = \dots = 0$ ; $B_{in} = B_{ji}$	

Table A-9 (continued)

Renon-Prausnitz (NRTL)	$\frac{\sum_i \tau_n G_n x_i}{\sum_s G_s x_s} + \sum_i \frac{x_r G_r}{\sum_s G_s x_s} \left( \tau_{i_r} - \frac{\sum_j \tau_j G_j x_i}{\sum_i G_i x_s} \right)$	$\tau_n = 0; \bar{G}_n = 0$ $(\tau_x - \tau_{i_r}) = (\tau_n - \tau_{i_r}) - (\tau_n - \tau_x)$
Wilson (equation does not follow from the Chien-Null equation)	$1 - \ln \left( \sum_s x_s A_s \right) - \sum_i \frac{x_i A_i}{\sum_s x_s A_s}$	$\frac{A_x}{A_u} = \left( \frac{A_n}{A_{i_r}} \right) / \left( \frac{A_x}{A_n} \right)$

Note: Equations containing only binary constants are given. From the Chien-Null equation one can obtain:

the van Laar - Null equation, by assuming:  $V_{j_\mu} = S_{j_\mu} = \left| \frac{A_{j_\mu}}{A_{ij}} \right|^{\frac{1}{q}}$ ; the Wohl equation, by assuming:  $V_{j_\mu} = S_{j_\mu} = \frac{q_j}{q}$

the Scatchard - Hamer equation, by assuming:  $V_{j_\mu} = S_{j_\mu} = \frac{V^0}{V_j^0}$ ; the Margules equation, by assuming:  $V_{j_\mu} = S_{j_\mu} = 1$

<sup>1</sup> Hala E., *Chemicke listy*, 71, 338, 1977 (by permission).

Table A-10. Equations of continuity<sup>1</sup>**Rectangular coordinates**

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial y}(\rho v_y) + \frac{\partial}{\partial z}(\rho v_z) = 0$$

**Cylindrical coordinates**

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r}(\rho r v_r) + \frac{1}{r} \frac{\partial}{\partial \theta}(\rho v_\theta) + \frac{\partial}{\partial z}(\rho v_z) = 0$$

**Spherical coordinates**

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r}(\rho r^2 v_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\rho v_\theta \sin \theta) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \phi}(\rho v_\phi) = 0$$

<sup>1</sup> After Bird R. B., Stewart W. E., and Lightfoot E. N., *Transport Phenomena*, John Wiley, New York, 1960 (by permission).

Table A-11. Equations of motion<sup>1</sup>**1. Rectangular coordinates****a. General equation****x-component**

$$\rho \left( \frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} \right) = - \frac{\partial p}{\partial x} - \left( \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \right) + \rho g_x$$

**y-component**

$$\rho \left( \frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} \right) = - \frac{\partial p}{\partial y} - \left( \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} \right) + \rho g_y$$

**z-component**

$$\rho \left( \frac{\partial v_z}{\partial t} + v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + v_z \frac{\partial v_z}{\partial z} \right) = - \frac{\partial p}{\partial z} - \left( \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right) + \rho g_z$$

**b. Equation for Newtonian fluids at constant values of  $\rho$  and  $\mu$** 

(The Navier-Stokes equation)

**x-component**

$$\rho \left( \frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} \right) = - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2} \right) + \rho g_x$$

**y-component**

$$\rho \left( \frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z} \right) = - \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2} \right) + \rho g_y$$

**z-component**

$$\rho \left( \frac{\partial v_z}{\partial t} + v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + v_z \frac{\partial v_z}{\partial z} \right) = - \frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2} \right) + \rho g_z$$

Table A-11 (continued)

## 2. Cylindrical coordinates

## a. General equation

*r*-component

$$\rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} + v_z \frac{\partial v_r}{\partial z} \right) = - \frac{\partial p}{\partial r} - \left( \frac{1}{r} \frac{\partial(r\tau_{rr})}{\partial r} + \frac{1}{r} \frac{\partial \tau_{r\theta}}{\partial \theta} - \frac{\tau_{\theta\theta}}{r} + \frac{\partial \tau_{rz}}{\partial z} \right) + \rho g_r$$

*θ*-component

$$\rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_r v_\theta}{r} + v_z \frac{\partial v_\theta}{\partial z} \right) = - \frac{\partial p}{\partial \theta} - \left( \frac{1}{r^2} \frac{\partial(r^2 \tau_{r\theta})}{\partial r} + \frac{1}{r} \frac{\partial \tau_{\theta\theta}}{\partial \theta} + \frac{\partial \tau_{\theta z}}{\partial z} \right) + \rho g_\theta$$

*z*-component

$$\rho \left( \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right) = - \frac{\partial p}{\partial z} - \left( \frac{1}{r^2} \frac{\partial(r\tau_{rz})}{\partial r} + \frac{1}{r} \frac{\partial \tau_{z\theta}}{\partial \theta} + \frac{\partial \tau_{zz}}{\partial z} \right) + \rho g_z$$

b. Equation for Newtonian fluids at constant values of  $\rho$  and  $\mu$ *r*-component

$$\begin{aligned} \rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} + v_z \frac{\partial v_r}{\partial z} \right) &= \\ = - \frac{\partial p}{\partial r} + \mu \left[ \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial(rv_r)}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \theta^2} - \frac{2}{r^2} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial^2 v_r}{\partial z^2} \right] + \rho g_r \end{aligned}$$

*θ*-component

$$\begin{aligned} \rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_r v_\theta}{r} + v_z \frac{\partial v_\theta}{\partial z} \right) &= \\ = - \frac{1}{r} \frac{\partial p}{\partial \theta} + \mu \left[ \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial(rv_\theta)}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{2}{r^2} \frac{\partial v_r}{\partial \theta} + \frac{\partial^2 v_\theta}{\partial z^2} \right] + \rho g_\theta \end{aligned}$$

*z*-component

$$\rho \left( \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right) = - \frac{\partial p}{\partial z} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2} \right] + \rho g_z$$

## 3. Spherical coordinates

## a. General equation

*r*-component

$$\begin{aligned} \rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial v_r}{\partial \phi} - \frac{v_\theta^2 + v_\phi^2}{r} \right) &= \\ = - \frac{\partial p}{\partial r} - \left( \frac{1}{r^2} \frac{\partial(r^2 \tau_{rr})}{\partial r} + \frac{1}{r \sin \theta} \frac{\partial(\tau_{r\theta} \sin \theta)}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial \tau_{r\phi}}{\partial \phi} - \frac{\tau_{\theta\theta} + \tau_{\phi\phi}}{r} \right) + \rho g_r \end{aligned}$$

Table A-11 (continued)

 **$\theta$ -component**

$$\rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial v_\theta}{\partial \phi} + \frac{v_r v_\theta}{r} - \frac{v_\phi^2 \cot \theta}{r} \right) = \\ = -\frac{1}{r} \frac{\partial p}{\partial \theta} - \left( \frac{1}{r^2} \frac{\partial(r^2 \tau_{rr})}{\partial r} + \frac{1}{r \sin \theta} \frac{\partial(\tau_{\theta\theta} \sin \theta)}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\phi}}{\partial \phi} + \frac{\tau_{rr}}{r} - \frac{\tau_{\phi\phi} \cot \theta}{r} \right) + \rho g_\theta$$

 **$\phi$ -component**

$$\rho \left( \frac{\partial v_\phi}{\partial t} + v_r \frac{\partial v_\phi}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\phi}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial v_\phi}{\partial \phi} + \frac{v_\theta v_r}{r} + \frac{v_\theta v_\phi \cot \theta}{r} \right) = \\ = -\frac{1}{r \sin \theta} \frac{\partial p}{\partial \phi} - \left( \frac{1}{r^2} \frac{\partial(r^2 \tau_{rr})}{\partial r} + \frac{1}{r} \frac{\partial \tau_{\theta\theta}}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial \tau_{\phi\phi}}{\partial \phi} + \frac{\tau_{rr}}{r} + \frac{2 \tau_{\theta\theta} \cot \theta}{r} \right) + \rho g_\phi$$

**b. Equation for Newtonian fluids at constant values of  $\rho$  and  $\mu$**  **$r$ -component**

$$\rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_r}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial v_r}{\partial \phi} - \frac{v_\theta^2 + v_\phi^2}{r} \right) = \\ = -\frac{\partial p}{\partial r} + \mu \left( \nabla^2 v_r - \frac{2}{r^2} v_r - \frac{2}{r^2} \frac{\partial v_\theta}{\partial \theta} - \frac{2}{r^2} v_\theta \cot \theta - \frac{2}{r^2 \sin \theta} \frac{\partial v_\phi}{\partial \phi} \right) + \rho g_r$$

 **$\theta$ -component**

$$\rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial v_\theta}{\partial \phi} + \frac{v_r v_\theta}{r} - \frac{v_\phi^2 \cot \theta}{r} \right) = \\ = -\frac{1}{r} \frac{\partial p}{\partial \theta} + \mu \left( \nabla^2 v_\theta + \frac{2}{r^2} \frac{\partial v_r}{\partial \theta} - \frac{v_\theta}{r^2 \sin^2 \theta} - \frac{2 \cot \theta}{r^2 \sin \theta} \frac{\partial v_\phi}{\partial \phi} \right) + \rho g_\theta$$

 **$\phi$ -component**

$$\rho \left( \frac{\partial v_\phi}{\partial t} + v_r \frac{\partial v_\phi}{\partial r} + \frac{v_\theta}{r} \frac{\partial v_\phi}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial v_\phi}{\partial \phi} + \frac{v_\theta v_r}{r} + \frac{v_\theta v_\phi \cot \theta}{r} \right) = \\ = -\frac{1}{r \sin \theta} \frac{\partial p}{\partial \phi} + \mu \left( \nabla^2 v_\phi + \frac{2}{r^2 \sin^2 \theta} \frac{\partial v_r}{\partial \phi} + \frac{2 \cot \theta}{r^2 \sin \theta} \frac{\partial v_\theta}{\partial \phi} - \frac{v_\phi}{r^2 \sin^2 \theta} \right) + \rho g_\phi$$

$$\nabla^2 = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2}{\partial \phi^2}$$

<sup>1</sup> After Bird R. B., Stewart W. E., and Lightfoot E. N., *Transport Phenomena*, John Wiley, New York, 1960 (by permission).

Table A-12. Equations for free settling

Spherical particles	Nonspherical particles
<u>Stokes law range</u>	
$Re < 0.4$	$Re < 0.05 + 0.4$ (depending on $\psi$ )
$\lambda = \frac{24}{Re}$	$\lambda = \frac{24}{Re} \frac{1}{0.843 \log(\psi/0.065)}$
$u = \frac{d^2 (\rho_s - \rho) g}{18\mu}$	$u = \frac{d_s^2 (\rho_s - \rho) g 0.843 \log(\psi/0.065)}{18\mu}$
<u>Allen law range</u>	
$2 < Re < 500$	
$\lambda = \frac{18.5}{Re^{0.6}}$	$\lambda = f(Re, \psi)$
$u = \frac{0.153 d^{1.14} (\rho_s - \rho)^{0.71} g^{0.71}}{\rho^{0.29} \mu^{0.43}}$	$u = f(d_s, \rho_s, \rho, \mu, \psi)$
<u>Newton law range</u>	
$Re > 1000$	$Re > 1000 + 2000$ (depending on $\psi$ )
$\lambda = 0.44$	$\lambda = 5.32 - 4.88\psi$
$u = 1.74 \left[ \frac{d(\rho_s - \rho) g}{\rho} \right]^{1/2}$	$u = 1.74 \left[ \frac{d_s(\rho_s - \rho) g}{\rho(12.1 - 11.1\psi)} \right]^{1/2}$

Table A-13. Energy equations for fluids with constant values of  $\rho$ ,  $\mu$ , and  $\lambda$ <sup>1</sup>

## 1. Rectangular coordinates

$$\rho c_p \left( \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) = \lambda \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] + 2\mu \left[ \left( \frac{\partial v_x}{\partial x} \right)^2 + \left( \frac{\partial v_y}{\partial y} \right)^2 + \left( \frac{\partial v_z}{\partial z} \right)^2 \right] + \mu \left\{ \left( \frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right)^2 + \left( \frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x} \right)^2 + \left( \frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y} \right)^2 \right\}$$

## 2. Cylindrical coordinates

$$\rho c_p \left( \frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} \right) = \lambda \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right] + 2\mu \left[ \left( \frac{\partial v_r}{\partial r} \right)^2 + \left( \frac{1}{r} \left( \frac{\partial v_\theta}{\partial \theta} + v_r \right) \right)^2 \right] + \left( \frac{\partial v_z}{\partial z} \right)^2 + \left( \frac{\partial v_r}{\partial \theta} + \frac{1}{r} \frac{\partial v_\theta}{\partial r} \right)^2 + \left( \frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} \right)^2 + \left[ \frac{1}{r} \frac{\partial v_r}{\partial \theta} + r \frac{\partial}{\partial r} \left( \frac{v_\theta}{r} \right) \right]^2$$

## 3. Spherical coordinates

$$\rho c_p \left( \frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial T}{\partial \phi} \right) = \lambda \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial}{\partial \theta} \left( \frac{\sin \theta}{r} \frac{\partial T}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 T}{\partial \phi^2} \right] + 2\mu \left\{ \left( \frac{\partial v_r}{\partial r} \right)^2 + \left( \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + v_r \right)^2 + \left( \frac{\partial v_\phi}{\partial \phi} \right)^2 + \left[ \frac{\sin \theta}{r} \frac{\partial v_r}{\partial \theta} + r \frac{\partial}{\partial r} \left( \frac{v_\theta}{r} \right) \right]^2 + \left[ \frac{\sin \theta}{r \sin \theta} \frac{\partial v_\theta}{\partial \phi} + r \frac{\partial}{\partial \theta} \left( \frac{v_\phi}{r} \right) \right]^2 \right\}$$

Notes: 1. Constancy of  $\rho$  results in equality  $c_p = c_v$ . 2. The terms in braces are related to viscous dissipation of work and are usually denoted by  $\Phi$ .

<sup>1</sup> After Bird R. B., Stewart W. E., and Lightfoot E. N., *Transport Phenomena*, John Wiley, New York, 1960 (by permission).

Table A-14. Forms of energy equation<sup>1</sup>

- 
1. General equation of energy at a constant value of  $\lambda$

$$\rho c_p \frac{DT}{Dt} = \lambda \nabla^2 T + q_v + T\beta \frac{Dp}{Dt} + \mu\Phi$$

2. For a gas,  $\beta = 1/T$  (as for an ideal gas)

$$\rho c_p \frac{DT}{Dt} = \lambda \nabla^2 T + q_v + \frac{Dp}{Dt} + \mu\Phi$$

3. For an incompressible fluid,  $\beta = 0$

$$\rho c_p \frac{DT}{Dt} = \lambda \nabla^2 T + q_v + \mu\Phi$$

4. For a motionless continuum

$$\rho c_p \frac{DT}{Dt} = \lambda \nabla^2 T + q_v$$

Notation:

Rectangular coordinates

$$\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}$$

Cylindrical coordinates

$$\nabla^2 T = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2}$$

Spherical coordinates

$$\nabla^2 T = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r^2 \sin\theta} \frac{\partial}{\partial \theta} \left( \sin\theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{r^2 \sin^2\theta} \frac{\partial^2 T}{\partial \phi^2}$$


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<sup>1</sup> Rhosenow W. M., and Choi H., *Heat, Mass and Momentum Transfer*, Prentice Hall, New York, 1961.

Table A-15. Equations of continuity for a component of mixture<sup>1</sup>

- 
1. General equation

- a. Rectangular coordinates

$$\frac{\partial c_A}{\partial x} + \left( \frac{\partial N_{A_x}}{\partial x} + \frac{\partial N_{A_y}}{\partial y} + \frac{\partial N_{A_z}}{\partial z} \right) = R_A$$

- b. Cylindrical coordinates

$$\frac{\partial c_A}{\partial x} + \left( \frac{1}{r} \frac{\partial(rN_{A_r})}{\partial r} + \frac{\partial N_{A_\theta}}{\partial \theta} + \frac{\partial N_{A_z}}{\partial z} \right) = R_A$$

- c. Spherical coordinates

$$\frac{\partial c_A}{\partial x} + \left( \frac{1}{r^2} \frac{\partial(r^2 N_{A_r})}{\partial r} + \frac{1}{r \sin\theta} \frac{\partial(N_{A_\theta} \sin\theta)}{\partial \theta} + \frac{1}{r \sin\theta} \frac{\partial N_{A_\phi}}{\partial \phi} \right) = R_A$$


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Table A-15. (continued)

2. Equation at constant values of  $\rho$  and  $D_{AB}$ 

## a. Rectangular coordinates

$$\frac{\partial c_A}{\partial t} + \left( v_x \frac{\partial c_A}{\partial x} + v_y \frac{\partial c_A}{\partial y} + v_z \frac{\partial c_A}{\partial z} \right) = D_{AB} \left( \frac{\partial^2 c_A}{\partial x^2} + \frac{\partial^2 c_A}{\partial y^2} + \frac{\partial^2 c_A}{\partial z^2} \right) + R_A$$

## b. Cylindrical coordinates

$$\frac{\partial c_A}{\partial t} + \left( v_r \frac{\partial c_A}{\partial r} + \frac{v_\theta}{r} \frac{\partial c_A}{\partial \theta} + v_z \frac{\partial c_A}{\partial z} \right) = D_{AB} \left( \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial c_A}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 c_A}{\partial \theta^2} + \frac{\partial^2 c_A}{\partial z^2} \right) + R_A$$

## c. Spherical coordinates

$$\begin{aligned} \frac{\partial c_A}{\partial t} + \left( v_r \frac{\partial c_A}{\partial r} + \frac{v_\theta}{r} \frac{\partial c_A}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial c_A}{\partial \phi} \right) &= \\ &= D_{AB} \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial c_A}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial c_A}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 c_A}{\partial \phi^2} \right] + R_A \end{aligned}$$

<sup>1</sup> After Bird R. B., Stewart W. E., and Lightfoot E. N., *Transport Phenomena*, John Wiley, New York, 1960 (by permission).

Table A-16. Forms of mass transfer equation<sup>1</sup>1. General equation for incompressible fluid at constant value of  $D_{AB}$ 

$$\frac{Dc_A}{Dt} = D_{AB} \nabla^2 c_A + R_A$$

## 2. For nonreacting systems

$$\frac{Dc_A}{Dt} = D_{AB} \nabla^2 c_A$$

## 3. For steady-state convection (rectangular coordinates)

$$v_x \frac{\partial c_A}{\partial x} + v_y \frac{\partial c_A}{\partial y} + v_z \frac{\partial c_A}{\partial z} = D_{AB} \nabla^2 c_A$$

## 4. For a motionless continuum

$$\frac{\partial c_A}{\partial t} = D_{AB} \nabla^2 c_A$$

Notation:

## Rectangular coordinates

$$\nabla^2 c_A = \frac{\partial^2 c_A}{\partial x^2} + \frac{\partial^2 c_A}{\partial y^2} + \frac{\partial^2 c_A}{\partial z^2}$$

## Cylindrical coordinates

$$\nabla^2 c_A = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial c_A}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 c_A}{\partial \theta^2} + \frac{\partial^2 c_A}{\partial z^2}$$

Table A-16. (continued)

## Spherical coordinates

$$\nabla^2 c_A = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial c_A}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial c_A}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 c_A}{\partial \phi^2}$$

<sup>1</sup> After Bird R. B., Stewart W. E., and Lightfoot E. N., *Transport Phenomena*, John Wiley, New York, 1960 (by permission).

Table A-17. Equations for steady-state diffusion

## 1. Equimolar counterdiffusion

$$\begin{aligned} a) \quad N_{Ax} &= -D_{AB} \frac{dc_A}{dx} & b) \quad N_{Ax} &= \frac{D_{AB}}{x_2 - x_1} (c_{A1} - c_{A2}) \\ N_{Ax} &= -\frac{D_{AB}}{RT} \frac{dp_A}{dx} & N_{Ax} &= \frac{D_{AB}}{RT(x_2 - x_1)} (p_{A1} - p_{A2}) \\ N_{Ax} &= -c D_{AB} \frac{dy_A}{dx} & N_{Ax} &= \frac{c D_{AB}}{x_2 - x_1} (y_{A1} - y_{A2}) \end{aligned}$$

## 2. Diffusion through a stationary component

$$\begin{aligned} a) \quad N_{Ax} &= -\frac{c D_{AB}}{c - c_A} \frac{dc_A}{dx} & b) \quad N_{Ax} &= \frac{c D_{AB}}{(x_2 - x_1) c_{Bm}} (c_{A1} - c_{A2}) \\ N_{Ax} &= -\frac{P D_{AB}}{RT(P - p_A)} \frac{dp_A}{dx} & N_{Ax} &= \frac{P D_{AB}}{RT(x_2 - x_1) p_{Bm}} (p_{A1} - p_{A2}) \\ N_{Ax} &= -\frac{c D_{AB}}{1 - y_A} \frac{dy_A}{dx} & N_{Ax} &= \frac{c D_{AB}}{(x_2 - x_1) y_{Bm}} (y_{A1} - y_{A2}) \end{aligned}$$

Table A-18. Relationships between the mass transfer coefficients (film model)

Equimolar counterdiffusion	Diffusion through a stationary component
$k_c = \frac{D_{AB}}{\delta}; \quad k_p = \frac{D_{AB}}{RT\delta}; \quad k_y = \frac{D_{AB}c}{\delta}$	$k'_c = \frac{D_{AB}c}{\delta c_{Bm}}; \quad k'_p = \frac{D_{AB}P}{RT\delta p_{Bm}}; \quad k'_y = \frac{D_{AB}c}{\delta y_{Bm}}$
$k_c = k_p RT = k_y \frac{1}{c} = k'_c \frac{c_{Bm}}{c} = k'_p RT \frac{P_{Bm}}{P} = k'_y \frac{y_{Bm}}{c};$	$c = \frac{P}{RT} = \frac{\rho}{M_m}; \quad \frac{c}{c_{Bm}} = \frac{P}{P_{Bm}}$
$Sh = \frac{k_c L}{D_{AB}} = \frac{k_p LRT}{D_{AB}} = \frac{k_y L}{D_{AB}c} = \frac{k'_c L c_{Bm}}{D_{AB}c} = \frac{k'_p LRT P_{Bm}}{D_{AB}P} = \frac{k'_y L y_{Bm}}{D_{AB}c}$	
$j_d = \frac{k_c}{u} Sc^{2/3} = \frac{k_p RT}{u} Sc^{2/3} = \frac{k_y M_m}{u\rho} Sc^{2/3} = \frac{k'_c M_m c_{Bm}}{u\rho} Sc^{2/3} = \frac{k'_p M_m P_{Bm}}{u\rho} Sc^{2/3} = \frac{k'_y M_m y_{Bm}}{u\rho} Sc^{2/3}$	

Table A-19. List of equations defining the Reynolds number for different flow types

Type of flow	Definition of the Reynolds number	Laminar flow $Re <$	Turbulent flow $Re >$	Limiting values	Notation	Remarks
1 Fluid flow through a pipe	$\frac{ud}{v}$	2100	3100	$u$ -mean fluid velocity $d$ -pipe diameter $v$ -kinematic viscosity of fluid		
2 Fluid flow through a conduit or channel with a noncircular cross section	$\frac{ud_n}{v}$	~2100	~3100	$u$ and $v$ as above $d=4r_h$ -hydraulic diameter of a pipe or a channel or of a pipe or a channel $o$ -wetted perimeter	$r_h = f/o$ -hydraulic radius $f$ -cross-sectional area of the stream $o$ -wetted perimeter	
3 Flow of a Bingham fluid through a pipe	$\frac{udp}{\mu_p}$	limiting values are depending on He; for $He < 10^3$ : 2100	3100	$u, d$ -as above $p$ -fluid density $\mu_p$ -apparent viscosity	He-Hedström number	
4 Flow of a generalized Newtonian fluid through a pipe	$\frac{u^{2-n'}d^{n'}}{k'g^{n'-1}}$	~2100	~3100	$u, d$ , $p$ -as above $n'$ , $k'$ -characteristic fluid parameters	for power-law fluids: $n' = n$ , $k' = k \left( \frac{3n+1}{4n} \right)^n$	
5 Gravitational liquid film flow	$\frac{4\Gamma}{\mu}$	25	1500	$\Gamma$ -mass flow rate related to the unit width of the film $\mu$ -liquid viscosity	flow is pseudolaminar at $25 < Re < 1000$ (waves appear on the film surface)	
6 Flow along a plate	$\frac{uL}{v}$	~2.10 <sup>5</sup>	~3.10 <sup>6</sup>	$u_0$ -fluid velocity $L$ -distance measured from the plate edge $v$ -kinematic viscosity of fluid	limiting values of $Re$ to some extent depend on the surface roughness	

Table A-19. (continued)

Type of flow	Definition of the Reynolds number	Laminar flow $Re <$	Turbulent flow $Re >$	Notation	Remarks
7 Motion or flow round a rigid spherical body	$\frac{ud}{v}$	0.4	1000	$u$ -solid velocity $d$ -solid particle diameter $v$ -continuous phase kinematic viscosity	in bubbling a limiting value between laminar and turbulent bubble motion is assumed at $Re=9$
8 Fluid flow through a packed bed	$\frac{u_0 d_{eq}}{\sqrt{(1-\varepsilon)}}$	10	100	$u_0$ -superficial fluid velocity $d_{eq}$ -equivalent diameter of packing elements $v$ -kinematic viscosity of fluid $\varepsilon$ -packing porosity	related to the equivalent capillary
	or			$Re_{eq} = \frac{u_0 d_{eq}}{v}$	equivalent
9 Flow of a generalized Newtonian fluid through a bed of spherical elements	$\frac{u_0^{2-n'} d^{n'} \rho \left( \frac{\varepsilon^2}{12} \right)^{n'-1}}{k' (1-\varepsilon)^{n'}} \quad n' > 1$	~10	~100	$u_0, \varepsilon$ -as above $n', k', \rho$ -as in p. 4 $d$ -diameter of bed elements	cf. remark in p. 4

Table A-20. Some correlations to calculate the heat transfer coefficients

Type of flow	Correlation	Range	Remarks
1 Laminar flow of fluid through a pipe - heat transfer between fluid and wall	$Nu = 3.66 + \frac{0.0668 Pe \frac{d}{L}}{1 + 0.04 \left( Pe \frac{d}{L} \right)^{2/3}}$	$Pe \frac{d}{L} < 10^4$	$T_w = \text{const.}$ (Hausen equation)
	$Nu_x = 4.36 + \frac{0.023 Pe \frac{d}{L}}{1 + 0.0012 Pe \frac{d}{L}}$	$q = \text{const.}$	(Hausen equation)
	$Nu_a = 1.62 \left( Pe \frac{d}{L} \right)^{1/3}$	$Pe \frac{d}{L} > 13$	$T_w = \text{const.}$ (approximated solution of Graetz)
	$Nu_a = 1.86 \left( Pe \frac{d}{L} \right)^{1/3} \left( \frac{\mu}{\mu_w} \right)^{0.14}$	$Pe \frac{d}{L} > 13$	$T_w = \text{const.}$ (empirical correlation with the Sieder-Tate correction)
	$Nu_a = 1.75 \left( \frac{3n' + 1}{4n'} Gz \right)^{1/3} \left( \frac{k'_w}{k'_v} \frac{8^{n'-n'_v}}{Gz} \right)^{0.14}$	$0.65 < Re' < 2100$ $100 < Gz < 2050$ $0.2 < n' < 0.7$	$T_w = \text{const.}$ (approximation due to Lévéque for non-Newtonian fluids with the Sieder-Tate correction)
	$Nu_a = 1.75 \left[ Gz + 0.0083 (Gr Pr)^{1/4} \right]^{1/3} \left( \frac{\mu}{\mu_w} \right)^{0.14}$	$10^{-2} < Pr \frac{d}{L} < 1$	$T_w = \text{const.}$ (correlation accounting for natural convection)

Table A-20. (continued)

Type of flow	Correlation	Range	Remarks
2 Turbulent flow of fluid through a pipe - heat transfer between fluid and wall	$Nu = 0.015 Re^{0.83} Pr^{0.42} \left( \frac{\mu}{\mu_w} \right)^{0.14}$ $Nu = 0.023 Re^{0.8} Pr^{0.33} \left( \frac{\mu}{\mu_w} \right)^{0.14}$ $Nu = 0.023 (Re^*)^{0.8} (Pr)^{0.33} \left( \frac{k'}{k'_w} g^{r^*-r_w^*} \right)^{0.14}$ $Nu = 0.023 Re^{0.8} Pr^{0.33} \left[ 1 - \frac{2 He}{0.023 Re^{0.8}} \left( \frac{\mu_p}{\mu_i} \right)^{0.12} \right]^3$ $\frac{\lambda_e}{\lambda_i} = \frac{2 + \left( \frac{\lambda_x}{\lambda_i} - 1 \right) \phi}{2 + (k-1)\phi} \cdot \frac{2(1-\phi) + k \frac{\lambda_x}{\lambda_i} \phi}{2(1-\phi) + k \phi}$	$2.3 \cdot 10^3 < Re < 10^4$ $0.5 < Pr < 600$ $\frac{L}{d} > 60; Re > 10^4$ $0.7 < Pr < 1.67 \cdot 10^4$	(Friend and Metzner formula)  for non-Newtonian fluids: $Pr^* = \frac{c_p k'}{\lambda} \left( \frac{8u}{d} \right)^{n-1}$  for suspension described by the Bingham equation; $\mu_p$ -plastic viscosity $\lambda_e$ -effective suspension thermal conductivity $\phi$ -volumetric fraction of solid; $k$ -coefficient dependent on shape of suspension; for spherical particles: $k = \frac{3}{2 + \frac{\lambda_e}{\lambda_i}}$

$$\begin{aligned}
Nu &= 0.0097 Re^{0.9} Pr^{1/2} f(Pr) \\
f(Pr) &= 1.10 + 0.44 Pr^{-1/3} - 0.70 Pr^{-11/6}
\end{aligned}$$

$T_{nom} = T_b$   
(Pinczewski and Sideman equations)

Table A-20. (continued)

Type of flow	Correlation	Range	Remarks
3 Turbulent flow of liquid metal through a pipe	$\text{Nu} = \frac{0.0097 \text{Re}^{9/10} \text{Pr}^{1/2} f(\text{Pr})}{1 + 0.064 \text{Pr}^{1/2} f(\text{Pr})}$ $f(\text{Pr}) = 1.10 + 0.44 \text{Pr}^{-1/3} - 0.70 \text{Pr}^{-1/6}$ $\text{Nu} = 0.0102 \text{Re}^{9/10} \text{Pr}^{1/3}$	$10 < \text{Pr} < 10^3$ $\text{Pr} > 10^3$	
4 Gravitational liquid flow along a vertical wall	$\text{Nu} = 5 + 0.025 \text{Pe}^{0.8}$ $\text{Nu} = 7 + 0.025 \text{Pe}^{0.8}$	$\text{Pe} > 100$ $\frac{L}{d} > 60$	$T_w = \text{const.}$ $q = \text{const.}$
5 Fluid flow along a plate - for the range of laminar boundary layer	$\text{Nu}_x = 0.67 \text{Re}_{eq}^{1/9} \left( \text{Pr} \frac{\delta_{eq}}{L} \right)^{1/3}$ $\text{Nu} = 0.01 (\text{Re}_{eq} \text{Pr})^{1/3}$	$\text{Re}_{eq} < 2100$ $\text{Re}_{eq} > 2100$	$\text{Nu} = \frac{\alpha \delta_{eq}}{\lambda}$ $\delta_{eq} = \left( \frac{v^2}{g} \right)^{1/3}$
6 Fluid flow along a plate - for the range of turbulent boundary layer	$\text{Nu}_x = 0.0292 \text{Re}^{4/5} \text{Pr}$ $\text{Nu} = 0.0365 \text{Re}^{4/5} \text{Pr}$	$T_w = \text{const.}; \quad T_{num} = T_b$	equation obtained under assumption that turbulent boundary layer extends over the entire plate

Table A-20. (continued)

Type of flow	Correlation	Range	Remarks
7 Fluid flow perpendicular to the cylinder axis	$Nu = (0.4Re^{1/2} + 0.06Re^{2/3})Pr^{0.4} \left( \frac{\mu}{\mu_w} \right)^{1/4}$	$1 < Re < 10^3$ $0.67 < Pr < 300$	$T_{\text{con}} = T_0$
8 Flow round the sphere	$Nu = 2 + 0.6Re^{1/2} Pr^{1/3}$ $Nu = 2 + (0.4Re^{1/2} + 0.06Re^{2/3})Pr^{0.4} \left( \frac{\mu}{\mu_w} \right)^{1/4}$	$1 < Re < 7 \cdot 10^4$ $0.6 < Pr < 400$ $3.5 < Re < 7.6 \cdot 10^4$ $0.7 < Pr < 380$	$T_{\text{con}} = T_0$
9 Flow of gas through a packed pipe - heat transfer between gas and wall	$Nu = 0.813Re^{0.9} \exp \left( -\frac{6d_{eq}}{d} \right)$ $(\text{heat transfer from the wall to gas})$ $Nu = 3.5 \exp \left( -\frac{4.6d_{eq}}{d} \right)$ $(\text{heat transfer from the wall to gas})$	$Re > 250$ $\frac{d_{eq}}{d} < 0.35$	$Nu = \frac{\alpha d}{\lambda}; \quad Re = \frac{G_0 d_{eq}}{\mu}$ $d$ -pipe diameter $d_{eq}$ -equivalent diameter of the bed elements
10 Liquid flow through a pipe filled with spheres or rings - heat transfer between liquid and wall	$Nu = 0.41 - 0.5 \frac{d_{eq}}{d} Re^{0.4} Pr^{0.33} \left( \frac{\mu}{\mu_w} \right)^{0.14}$	$3 \cdot 10^3 < Re < 4 \cdot 10^4$ $0.07 < \frac{d_{eq}}{d} < 0.3$	$Nu = \frac{\alpha d}{\lambda}; \quad Re = \frac{G_0 d_{eq}}{\mu}$ $d$ -pipe diameter $d_{eq}$ -equivalent diameter of the bed elements
11 Fluid flow through the packing - heat transfer between fluid and packing elements	$Nu = 0.91 \psi Re^{0.49} Pr^{0.33}$ $Nu = 0.61 \psi Re^{0.49} Pr^{0.33}$	$Re < 50$ $Re > 50$	$Nu = \frac{\alpha}{\lambda \alpha \psi}; \quad Re = \frac{G_0}{\mu \alpha \psi}$ packing type $\psi$ spheres 1.00 cylinders 0.91 Rasching rings 0.79 Berl saddles 0.80

Table A-20. (continued)

Type of flow	Correlation	Range	Remarks
12 Fluid flow through the packing - heat transfer between fluid and packing elements	$\text{Nu} = (0.4\text{Re}^{1/2} + 0.2\text{Re}^{2/3})\text{Pr}^{0.4}$	$3.7 < \text{Re} < 8 \cdot 10^3$	$\text{Nu} = \frac{\alpha d_{eq}}{\lambda(1-\varepsilon)}; \quad \text{Re} = \frac{G_d d_{eq}}{\mu(1-\varepsilon)}$
	$j_{fr} = 5.7\text{Re}^{-0.78}$	$1 < \text{Re} < 30$	for a fluidized packing:
	$j_{fr} = 1.77\text{Re}^{-0.44}$	$30 < \text{Re} < 2 \cdot 10^4$	$j_{fr} = \frac{\alpha}{c_p G_0} \text{Pr}^{2/3}$
13 Natural convection in an infinite space - for a plate, a cylinder, and a sphere	$\text{Nu} = 1.18(\text{GrPr})^{1/8}$ $\text{Nu} = 0.54(\text{GrPr})^{1/4}$ $\text{Nu} = 0.135(\text{GrPr})^{1/3}$	$10^{-3} < \text{GrPr} < 5 \cdot 10^2$ $5 \cdot 10^2 < \text{GrPr} < 2 \cdot 10^7$ $2 \cdot 10^7 < \text{GrPr} < 10^3$	$T_{\text{mean}} = T_{bu}$ characteristic linear dimension: horizontal plate-width, vertical plate and vertical cylinder-height, horizontal cylinder and sphere-diameter
	$\text{Nu} = 2 + 0.282(\text{GrPr})^{0.37}$	$\text{GrPr} < 10^2$	
	$\text{Nu} = 2 + 0.5(\text{GrPr})^{0.25}$	$10^2 < \text{GrPr} < 10^6$	for a sphere

- Notes: 1. If not stated otherwise, dimensionless numbers are defined in accord with Tables A-19 and A-25.  
2. The Nusselt number without a subscript is related to the logarithmic mean driving force, the Nusselt number with subscript  $x$  is related to arithmetic mean driving force. Subscript  $x$  means the local value of Nusselt number.  
3. A nominal temperature at which fluid properties should be determined is denoted as  $T_{nom}$ . If there is no comment in remarks, the nominal temperature is equal to the mean fluid temperature.  
4. The meaning of the symbols used is as follows:  $q$ -heat flux,  $T_w$ -wall temperature,  $T_b$ -mean temperature of the boundary layer,  $T_0$ -bulk fluid temperature.

Table A-21. Some correlations to calculate the mass transfer coefficients

Type of motion	Transfer environment	Correlation	Range	Remarks
1 Laminar flow of fluid through a pipe - mass transfer between fluid and wall	fluid	$Sh = 3.66 + \frac{0.0668 Pe^{\frac{d}{L}}}{1 + 0.04 \left( Pe^{\frac{d}{L}} \right)^{1/3}}$	$Pe \frac{d}{L} < 10^4$	for a constant concentration value at the pipe wall (Hausen equation)
		$Sh_x = 4.36 + \frac{0.023 Pe^{\frac{d}{L}}}{1 + 0.012 Pe^{\frac{d}{L}}}$		for a constant mass flux at the pipe wall (Hausen equation)
		$Sh_o = 1.62 \left( Pe^{\frac{d}{L}} \right)^{1/3}$	$Pe \frac{d}{L} > 13$	for a constant concentration value at the pipe wall
2 Turbulent flow of fluid through a pipe - mass transfer between fluid and wall	fluid	$Sh = 0.023 Re^{0.83} Sc^{0.44}$	$2 \cdot 10^3 < Re < 3.5 \cdot 10^4$ $0.6 < Sc < 2.5$	(equation due to Gilliland and Sherwood)
		$Sh = 0.023 Re^{0.83} Sc^{0.33}$	$2 \cdot 10^4 < Re < 7 \cdot 10^4$ $9 \cdot 10^2 < Sc < 2.3 \cdot 10^3$	(equation due to Linton and Sherwood)
		$Sh = 0.0096 Re^{0.913} Sc^{0.346}$	$Sc >> 1$	(equation due to Harriot and Hamilton)
		$Sh = 0.0097 Re^{0.10} Sc^{1/2} f(Sc)$	$0.5 < Sc < 10$	
		$f(Sc) = 1.10 + 0.44 Sc^{-1/3} - 0.70 Sc^{-1/6}$	$10 < Sc < 10^3$	(equations due to Pinczewski and Sideman)
		$Sh = \frac{0.0097 Re^{0.10} Sc^{1/2} f(Sc)}{1 + 0.064 Sc^{1/2} f(Sc)}$		
		$f(Sc) = 1.10 + 0.44 Sc^{-1/3} - 0.70 Sc^{-1/6}$		
		$Sh = 0.0102 Re^{0.10} Sc^{1/3}$	$Sc > 10^3$	

Table A-21. (continued)

Type of motion	Transf. env.	Correlation	Range	Remarks
3 Gravitational liquid film flow along a vertical wall - mass transfer between gas and liquid	liquid	$Sh = 1.9 Re^{-1/3}$	$Re^{2/3} \left( Sc \frac{\delta_{eq}}{L} \right)^{1/2} < 2.62$	$\delta_{eq} = \left( \frac{v^2}{g} \right)^{1/3}$ ; $Sh = \frac{k_c \delta_{eq}}{D}$
4 Flow along a plate - mass transfer for the range of a laminar boundary layer	fluid	$Sh_x = 0.725 Re^{1/3} Sc \left( \frac{\delta_{eq}}{L} \right)^{1/2}$	$Re^{2/3} \left( Sc \frac{\delta_{eq}}{L} \right)^{1/2} > 2.62$	L-wall height linear dimension: distance from the plate edge
5 Flow along a plate - mass transfer for the range of a turbulent boundary layer	fluid	$Sh_x = 0.3332 Re^{1/2} Sc^{1/3}$ $Sh = 0.664 Re^{1/2} Sc^{1/3}$		equation obtained with an assumption that turbulent boundary layer extends over the entire plate
6 Gas flow perpendicular to a tube bundle	gas	$Sh = 0.281 Re^{1/3} Sc^{1/4}$	$4 \cdot 10^4 < Re < 2.5 \cdot 10^4$ $0.6 < Sc < 2.6$	linear dimension: pipe diameter
7 Flow round a sphere	fluid	$Sh = 2 + 0.6 Re^{1/2} Sc^{1/3}$		
8 Free fall of a drop through a gas	liquid (dispersed phase)	$Sh = 11.3 Fo^{-1/2}$ $Sh = 6.6$	$Fo < 0.0293$ $Fo > 0.0293$	for non-circulating drops
9 Motion of a spherical drop through a liquid continuous phase	liquid (continuous phase)	$Sh = 0.65 \left( \frac{\mu_c}{\mu_c + \mu_a} \right) Pe^{1/2}$ $Sh = 1.13 Pe^{1/2}$	$Re < 1$ $Pe \gg 1$ $Re \gg 1$	(Theoretical solution due to Levich for a creeping flow) (theoretical equation due to Boussinesq for a potential flow)

Table A-21. (continued)

Type of motion	Transf. env.	Correlation	Range	Remarks
10	Bubble motion through a liquid	$Sh = 5.52 \left( \frac{\mu_c + \mu_d}{2\mu_c + 3\mu_d} \right)^{0.036} \left( \frac{Re^2}{We} \right)^{0.036}$ $Sh = 2 + 0.569(GrSc)^{0.25}$ $+ 0.347(ReSc^{0.1})^{0.62}$	$Pe^{0.5}$ $3.6 \cdot 10^3 < Pe < 2.25 \cdot 10^4$	We-Weber number
	gas (dispersed phase)	$Sh = 6.6$	$Re < 9$	
	liquid (continuous phase)	$Sh = 0.998Pe^{1/2}$ $Sh = 2 + 0.57Re^{0.5}Sc^{0.35}$ $Sh = 0.65Pe^{1/2}$ $Sh = 1.13(1 - 2.9Re^{-1/2})^{1/2}Pe^{1/2}$ $Sh = 1.13Pe^{1/2}$ $Sh = 0.65 \left[ 1 - \frac{4n(n-1)}{2n+1} \right]^{1/2} Pe^{1/2}$ $Sh = 1.13Pe^{1/2}$	$(theoretical solution due to Levich)$ $(equation due to Griffith)$ $(theoretical solution due to Levich)$ $(equation due to Lochiel and Calderbank)$ $(theoretical solution due to Boussinesq)$ $(non-Newtonian power-law fluid flow)$ $(for circulating bubbles in form of bubble cap; Newtonian or$	

Table A-21. (continued)

Type of motion	Transf. env.	Correlation	Range	Remarks
11	Mixing of a suspension in a tank (e.g., dissolution)	liquid $\text{Sh} = 1.3 \text{Re}^{1/2} \text{Sc}^{1/3}$	$d_{\text{eq}} < 2.5 \text{ mm}$ $d_{\text{eq}} > 2.5 \text{ mm}$	non-Newtonian fluid flow, linear dimension: equivalent bubble diameter for mass transfer in stirred tanks, on sieve trays etc.; linear dimension: equivalent bubble diameter, $d_{\text{eq}}$ (Calderbank formulas)
12	Gas flow through a packing (particles or rings) dry or wetted (for two-phase flow)	gas $\text{Sh} = 0.31(\text{GrSc})^{1/3}$	$\frac{k_c d_t}{D}, \quad \text{Re} = \frac{N^{1/3} d^{1/3}}{\nu}$ $\text{Sh} = 0.42 \text{Gr}^{1/2} \text{Sc}^{1/2}$	$N_{\text{mix}}$ -power demand for mixing (related to a unit mass of suspension) $d$ -solid particle diameter (Reynolds number related to the flow conditions over a plate) $\frac{k_c d_t}{D}, \quad \text{Re} = \frac{nL^2}{\nu}$ $n$ -number of impeller rotations $d_t$ -tank diameter $L$ -impeller length (Reynolds number related to the impeller)
			$\text{Sh} = 0.05 \text{Re}^{0.33} \text{Sc}^{0.5}$	$\frac{k_c d_t}{D}, \quad \text{Re} = \frac{G_0}{\mu \sigma}$ $d$ -mean size of a particle or outer diameter of the ring $G_0$ -gas superficial mass veloc.

Table A-21. (continued)

Type of motion	Transf. env.	Correlation	Range	Remarks
13 Two-phase flow (gas and liquid flow gravitationally) through a packing (particles or rings)	liquid	$Sh = 0.015Re^{2/3} Sc^{1/3}$	$G_0 > 0.8 \text{ kg / (m}^2 \cdot \text{s)}$ (liquid superficial mass velocity)	$Sh = \frac{k \delta_{\text{eq}}}{D}; Re = \frac{G_0}{\mu a}$
14 Liquid flow through a packing (spherical particles)	liquid	$\varepsilon j_b = 1.0Re_h^{2/3}$ $\varepsilon j_b = 0.75Re_h^{-1/2}$	$10^{-3} < Re_h < 5$ $1.3 \cdot 10^3 < Sc < 18 \cdot 10^3$ $5 < Re_h < 10^2$	$Re = \frac{2u_b d_{\text{eq}}}{3\sqrt{(1-\varepsilon)}}; j_b = \frac{k_e \rho}{G_0} Sc^{2/3}$ (Miyauchi and Nomura equations)
15 Fluid flow through a packed or fluidized bed	fluid	$j_b = \frac{1.957}{Re^{0.02}} + \frac{1.685}{Re^{0.44}}$	$10^{-2} < Re < 3 \cdot 10^4$ (for gases $Re > 10$ )	$j_b = \frac{k_e \rho}{G_0} Sc^{2/3}$ (Dwivedi and Upadhyaya equation)
16 Fluid flow through a fluidized bed	fluid	$j_b = 5.7Re^{-0.78}$ $j_b = 1.77Re^{-0.44}$	$1 < Re < 30$ $30 < Re < 2 \cdot 10^4$	$j_b = \frac{k_e \rho}{G_0} Sc^{2/3}$ (equations due to Gelperin)
17 Natural convection - for spherical particles or drops in a fluid	fluid (continuous phase)	$Sh = 2 + 0.282(GrSc)^{0.37}$ $Sh = 2 + 0.5(GrSc)^{0.25}$	$GrSc < 10^2$ $10^2 < GrSc < 10^6$	

Notes: 1. If not stated otherwise, dimensionless numbers are defined in accord with Tables A-19 and A-25.

2. The Sherwood number without a subscript is related to the logarithmic mean driving force; the Sherwood number with subscript  $a$  is related to the arithmetic driving force. Subscript  $x$  means a local value of Sherwood number.

Table A-22. List of dimensionless parameters for heat and mass transfer

Mass transfer	Heat transfer
$Y = \frac{c_{A1} - c_A}{c_{A1} - c_{A0}}$	$Y = \frac{T_1 - T}{T_1 - T_0}$
<u>Fourier number</u>	<u>Fourier number</u>
$Fo = \frac{D_{AB}t}{x_1^2}$	$Fo = \frac{\alpha t}{x_1^2}$
<u>Biot number</u>	<u>Biot number</u>
$Bi = \frac{k_e x_1}{D_{AB}}$	$Bi = \frac{\alpha x_1}{\lambda}$
<u>Schmidt number</u>	<u>Prandtl number</u>
$Sc = \frac{\mu}{\rho D_{AB}} = \frac{v}{D_{AB}}$	$Pr = \frac{c_p \mu}{\lambda} = \frac{v}{\alpha}$
<u>Sherwood number</u>	<u>Nusselt number</u>
$Sh = \frac{k_e L}{D_{AB}}$	$Nu = \frac{\alpha L}{\lambda}$
<u>Grashof number</u>	<u>Grashof number</u>
$Gr = \frac{gL^3 \beta' \Delta c}{v^2}$	$Gr = \frac{gL^3 \beta \Delta T}{v^2}$
<u>Péclet number</u>	<u>Péclet number</u>
$Pe = Re Sc = \frac{uL}{D_{AB}}$	$Pe = Re Pr = \frac{uL}{\alpha}$
<u>Stanton number</u>	<u>Stanton number</u>
$St = \frac{Sh}{Re Sc} = \frac{k_e}{u}$	$St = \frac{Nu}{Re Pr} = \frac{\alpha}{c_p u \rho}$
$j_D = St Sc^{2/3}$	$j_H = St Pr^{2/3}$

Table A-23. Cases of mass transfer with an irreversible first order homogeneous chemical reaction (film model)

Reaction	Conditions		$k_c^*$	$\frac{k_c^*}{k_c}$
	$k_c$	Ha and $\alpha$		
1 Very slow	$k_c \gg \sqrt{k_1 D_A}$	Ha $\ll 1$	$k_c^* = \frac{v}{a} k_c$	$\frac{k_c^*}{k_c} = \alpha Ha^2$
	$k_c \gg \frac{v}{a} k_1$	$\alpha Ha^2 \ll 1$		
2 Slow	$k_c \gg \sqrt{k_1 D_A}$	Ha $\ll 1$	$k_c^* = k_c$	$\frac{k_c^*}{k_c} = 1$
	$k_c \ll \frac{v}{a} k_1$	$\alpha Ha^2 \gg 1$		
3 Intermediate case between 1 and 2	$k_c \gg \sqrt{k_1 D_A}$	Ha $\ll 1$	$k_c^* = \left( \frac{1}{k_c} + \frac{a}{vk_1} \right)^{-1}$	$\frac{k_c^*}{k_c} = \frac{\alpha Ha^2}{\alpha Ha^2 + 1}$
4 Fast	$k_c \ll \sqrt{k_1 D_A}$	Ha $\gg 1$	$k_c^* = \sqrt{k_1 D_A}$	$\frac{k_c^*}{k_c} = Ha$
5 Intermediate case between 2 and 4	-	-	-	$\frac{k_c^*}{k_c} = Ha \frac{(\alpha - 1)Ha + \tanh Ha}{(\alpha - 1)Ha \tanh Ha + 1}$

$$Ha = \frac{\sqrt{k_1 D_A}}{k_c}; \quad \alpha = \frac{v k_c}{a D_A}; \quad v - \text{the ratio of liquid volume to the total volume, } a - \text{the ratio of the interfacial area to the total volume.}$$

Table A-24. Cases of mass transfer with an irreversible second order homogeneous chemical reaction (film model)

Reaction	Conditions		$k_c^*$	$\frac{k_c^*}{k_c}$
	$k_c$	Ha, $\alpha, M$		
1 Very slow	$k_c \gg \sqrt{k_2 c_{B0} D_A}$	Ha $\ll 1$	$k_c^* = \frac{v}{a} k_2 c_{B0}$	$\frac{k_c^*}{k_c} = \alpha Ha^2$
	$k_c \gg \frac{v}{a} k_2 c_{B0}$	$\alpha Ha^2 \ll 1$		
2 Slow	$k_c \gg \sqrt{k_2 c_{B0} D_A}$	Ha $\ll 1$	$k_c^* = k_c$	$\frac{k_c^*}{k_c} = 1$
	$k_c \ll \frac{v}{a} k_2 c_{B0}$	$\alpha Ha^2 \gg 1$		
3 Intermediate case between 1 and 2	$k_c \gg \sqrt{k_2 c_{B0} D_A}$	Ha $\ll 1$	$k_c^* = \left( \frac{1}{k_c} + \frac{a}{vk_2 c_{B0}} \right)^{-1}$	$\frac{k_c^*}{k_c} = \frac{\alpha Ha^2}{\alpha Ha^2 + 1}$
4 Fast	$k_c \ll \sqrt{k_2 c_{B0} D_A}$	Ha $\gg 1$	$k_c^* = \sqrt{k_2 c_{B0} D_A}$	$\frac{k_c^*}{k_c} = Ha$
	$k_c(1+M) \gg \sqrt{k_2 c_{B0} D_A}$	Ha $\ll M$		
5 Instantaneous	$k_c(1+M) \ll \sqrt{k_2 c_{B0} D_A}$	Ha $\gg M$	$k_c^* = k_c(1+M)$	$\frac{k_c^*}{k_c} = 1+M$
6 Other cases	Van Krevelen and Hofstijzer diagram (C-22)			
	$Ha = \frac{\sqrt{k_2 c_{B0} D_A}}{k_c}; \quad \alpha = \frac{v k_c}{a D_A}; \quad M = \frac{c_{B0} D_B}{b c_A D_A}$			

Table A-25. Selected dimensionless numbers

No.	Dimensionless number	Definition	Physical interpretation	Applications
1	Archimedes number	$Ar = \frac{gL^3(\rho - \rho_d)}{v^2 \rho}$	A measure of the ratio of buoyancy force and internal friction force	Characterizes an effect of buoyancy force on settling or rising phenomena in fluids
2	Bingham number	$Bm = \frac{\tau_0 L}{\mu_p u}$	A measure of the ratio of shear stress to viscosity force in a Bingham fluid	Characterizes a Bingham fluid flow
3	Biot number	$Bi = \frac{\alpha L}{\lambda_s}$	A measure of the ratio of thermal resistance of solid to thermal resistance of fluid	Characterizes an effect of heat transfer conditions at the surface on the heating or cooling course of a solid
4	Bodenstein number	$Bo = \frac{uL}{D_L}$	A measure of the ratio of convective mass transfer rate to diffusive mass transfer rate (or dispersion rate)	Characterizes mass transfer (in particular dispersion) in reactors and mass exchangers; corresponds to the Pécelt number
5	Brinkman number	$Br = \frac{\mu u^2}{\lambda \Delta T}$	A measure of the ratio of heat generation due to internal friction in a fluid to heat transfer rate	Characterizes viscous fluid flow with heat generation due to internal friction
6	Capillary number	$Ka = \frac{K \Delta p}{L \sigma \cos \theta}$ $(K = \frac{u_0 \mu L}{\Delta p})$	A measure of the ratio of the external pressure forces and capillary forces	Characterizes wetting of porous solid by liquid; it serves to calculate maximum bound saturation
7	Cauchy number	$Ca = \frac{\rho u^2}{E}$	A measure of the ratio of internal force to elastic force	Characterizes flow of a compressible liquid
8	Damköhler number	$Da_1 = \frac{rL}{uc}$	A measure of the ratio of chemical reaction rate to convective mass transfer rate	Characterizes a course of chemical reaction in a continuous flow system
9	Damköhler number	$Da_{11} = \frac{rL^2}{Dc}$	A measure of the ratio of chemical reaction rate to diffusion rate	Characterizes an effect of diffusion on chemical reaction

Table A-25. (continued)

No.	Dimensionless number	Definition	Physical interpretation	Applications
10	Damköhler number	$Da_m = \frac{q_r rL}{c_p \rho u \Delta T}$	A measure of the ratio of heat generation rate due to chemical reaction to convective heat transfer rate	Characterizes an effect of heat convection on chemical reaction
11	Damköhler number	$Da_{IV} = \frac{q_r rL^2}{\lambda \Delta T}$	A measure of the ratio of heat generation due to chemical reaction to conductive heat transfer rate	Characterizes an effect of heat conduction on chemical reaction
12	Deborah number	$Deb = \frac{u \theta_r}{d_p}$	A measure of the ratio of relaxation time to time of deformation endurance	Characterizes a flow of viscoelastic fluids
13	Eötvös number	$Eo = \frac{gd_p^2(\rho_d - \rho)}{\sigma}$	A measure of the ratio of gravity force to surface tension force	Characterizes dispersion and disintegration of phases phenomena in a two-phase flow
14	Euler number	$Eu = \frac{\Delta p}{\rho u^2}$	A measure of the ratio of hydraulic resistance force to kinetic energy of a stream	Characterizes pressure drop in fluid flow; it denotes a criterion of a dynamic flow similarity
15	Fourier number	$Fo = \frac{at}{L^2}$	A relation between the variation rate of temperature field and physical properties and geometrical dimensions	Characterizes unsteady-state heat transfer (heating, cooling); it denotes a criterion of temperature field similarity
16	Fourier number (diffusive)	$Fo = \frac{Dt}{L^2}$	As above with respect to concentration field	Characterizes unsteady-state diffusion; it denotes a criterion of concentration field similarity
17	Froude number	$Fr = \frac{u^2}{gL}$	A measure of the ratio of inertial force to gravity force	Characterizes an effect of gravity force on fluid flow
18	Gallileo number	$Ga = \frac{Re^2}{Fr} = \frac{gL^3}{v^2}$	A measure of the ratio of gravity force to internal friction force	Characterizes an effect of gravity fluid flow

Table A-25. (continued)

No.	Dimensionless number	Definition	Physical interpretation	Applications
19	Graetz number	$Gz = \frac{W c_p}{\lambda l}$	A measure of the convective heat transfer rate to conductive heat transfer rate	Characterizes laminar heat transfer
20	Grashof number	$Gr = \frac{gL^3 \beta \Delta T}{v^2}$	A measure of the ratio of buoyancy force due to temperature difference at different fluid points to internal friction force	Characterizes natural (temperature) convection
21	Grashof number (diffusive)	$Gr = \frac{gL^3 \beta' \Delta c}{v^2}$	A measure of the ratio of buoyancy force due to concentration difference at different fluid points to internal friction force	Characterizes natural (concentration) convection
22	Hatta number	For $m, n$ -th order irreversible reaction: $Ha = \left( \frac{2}{m+1} k_{n,m} D_A c_{A,i}^{n-1} c_{B,j}^n \right)^{1/m}$	A relation between chemical reaction rate and mass transfer rate	Characterizes an effect of chemical reaction on mass transfer
23	Hedström number	$He = Re Bm = \frac{\tau_0 L^2 \rho}{\mu_p^2}$	A relation between shear stresses, viscosity forces, and inertial forces during a Bingham fluid flow	Characterizes Bingham fluid flow
24	Knudsen number	$Kn = \frac{\bar{l}}{L}$	A ratio of the mean free path of molecules to a characteristic linear size of the system	Characterizes gas flow in capillary under low pressure; it denotes a criterion of medium discontinuity
25	Lewis number	$Le = \frac{Sc}{Pr} = \frac{\alpha}{D}$	A ratio of the coefficient of thermal diffusivity to mass diffusivity; a measure of the ratio of the variation rate of temperature field to that of concentration field	Characterizes phenomena of simultaneous heat and mass transfer

Table A-25. (continued)

No.	Dimensionless number	Definition	Physical interpretation	Applications
26	Mach number	$Ma = \frac{u}{u_c}$	A ratio of flow velocity to the sonic velocity; a measure of the ratio of kinetic energy and internal energy of a gas	Characterizes gas flow at large velocities (effect of medium compressibility)
27	Nusselt number	$Nu = \frac{\alpha L}{\lambda}$	A measure of the ratio of heat transfer rate and conductive heat transfer rate	Characterizes heat transfer
28	Péclet number	$Pe = RePr = \frac{uL}{a}$	A measure of the ratio of convective heat transfer rate and conductive heat transfer rate	Characterizes heat transfer in a flowing fluid
29	Péclet number (diffusive)	$Pe = ReSc = \frac{uL}{D}$	A measure of the ratio of convective mass transfer rate and diffusion rate	Characterizes mass transfer in a flowing fluid
30	Power number	$Po = \frac{N}{L^5 n^3 \rho}$	A measure of the ratio of drag force and inertial force	Characterizes energy demand at mechanical agitation of liquids
31	Prandtl number	$Pr = \frac{\nu}{a}$	A measure of the ratio of molecular momentum transfer rate and conductive heat rate in a fluid	Characterizes a similarity of velocity and temperature fields in a flowing fluid; it denotes a similarity criterion of physical properties of substances during heat transfer
32	Reynolds number	$Re = \frac{uL}{\nu}$	A measure of the ratio of inertial force and internal friction force	Characterizes hydrodynamic similarity of fluid flow, it denotes a criterion of flow turbulence
33	Schmidt number	$Sc = \frac{\nu}{D}$	A measure of the ratio of molecular momentum transfer rate and diffusion rate	Characterizes a similarity of velocity and concentration fields in a flowing fluid; it denotes a similarity criterion

**370 EQUATION TABLES**

Table A-25. (continued)

No.	Dimensionless number	Definition	Physical interpretation	Applications
				of physical properties of substances during mass transfer
34	Sherwood number	$Sh = \frac{kL}{D}$	A measure of the ratio of mass transfer rate and diffusion rate	Characterizes mass transfer
35	Stanton number	$St = \frac{Nu}{Pe} = \frac{\alpha}{c_p u \rho}$	A measure of the ratio of heat transfer rate and convective heat transfer rate through a fluid stream	Characterizes heat transfer phenomena in a turbulent fluid flow
36	Stokes number	$Stk = \frac{ud_p^2 \rho_s}{\mu L}$	A measure of the ratio of inertial force and friction force acting on a particle moving in a fluid	Characterizes settling phenomena of solid in fluids
37	Strouhal number	$S = \frac{ut}{L}$	A measure of the ratio of variation rate of velocity field in a fluid	Characterizes unsteady-state fluid flow
38	Weber number	$We = \frac{u^2 L \rho}{\sigma}$	A measure of the ratio of inertial force and surface tension force	Characterizes an effect of surface tension on liquid flow or dispersion

## B. NUMERICAL TABLES

- |             |   |
|-------------|---|
| Table B-1   | Constants in the van der Waals equation of state  |
| Table B-2   | Constants in the Beattie-Bridgeman equation of state  |
| Table B-3a  | Group contributions to molar liquid volume at the normal boiling point<br>(according to Le Bas)   |
| Table B-3b  | Molar volumes of liquefied gases at the normal boiling point  |
| Table B-4   | Reduced liquid density (after Lydersen, Greenkorn, and Hougen)  |
| Table B-5   | Coefficients in the equation $C_p=a+bT+cT^2+dT^3$ [J/mol·K] for gases<br>(inorganic substances)   |
| Table B-6   | Coefficients in the equation $C_p=a+bT+cT^2+dT^3$ [J/mol·K] for gases<br>(organic substances)   |
| Table B-7   | Force parameters in the Lennard-Jones potential equation<br>(based on viscosities)  |
| Table B-8   | Functions in determination of nonpolar gas properties   |
| Table B-9   | Values of the function $f_1(T')$ in gas viscosity determination by the<br>Bromley and Wilke method  |
| Table B-10  | Correction factors for viscosity, $\mu$ , thermal conductivity, $\lambda$ , and<br>diffusivity, $D$ , of nonpolar gases                                 |
| Table B-11  | The Sutherland constants for some gases and vapors<br>(within the range 0-250°C)  |
| Table B-12  | Values of the function $\lambda/\mu_r=f(T_r)$ (low pressure)  |
| Table B-13  | Correction factors, $\beta$ , and solubility parameters, $\delta$ , in determination<br>of absorption equilibrium according to the method of Hildebrand |
| Table B-14  | Partial molar volumes of dissolved gases at 25°C  |
| Table B-15a | Partial molar volumes of dissolved gases at different temperatures  |
| Table B-15b | Apparent partial molar volumes of dissolved gases at different<br>temperatures  |
| Table B-16  | Contribution of ions and solutes in determination of the Henry's<br>constant  |
| Table B-17  | Values of functions $\Phi$ , $\Phi'$ , and $\Phi''$ in the solution due to Blasius for<br>flow along a flat, thin plate                                 |
| Table B-18  | Values of the constants in the heat transfer equation for laminar flow<br>of generalized Newtonian fluid  |

Table B-1. Constants in the van der Waals equation of state

Gas	$a$ [N·m <sup>4</sup> ·mol <sup>-2</sup> ]	$b \cdot 10^5$ [m <sup>3</sup> ·mol <sup>-1</sup> ]
H <sub>2</sub>	0.0247	2.66
He	0.0035	2.34
N <sub>2</sub>	0.1408	3.91
O <sub>2</sub>	0.1378	3.18
H <sub>2</sub> O	0.5796	3.19
NH <sub>3</sub>	0.4235	3.72
NO	0.1361	2.79
CH <sub>4</sub>	0.2283	4.28
CO	0.1509	3.99
CO <sub>2</sub>	0.3658	4.29

Table B-2. Constants in the Beattie-Bridgeman equation of state  
 $p$  [N/m<sup>2</sup>],  $T$  [K],  $V$  [m<sup>3</sup>/mol]

Gas		$A_0$	$a \cdot 10^3$	$B_0 \cdot 10^3$	$b \cdot 10^3$	$c$
Air	-	0.13186	0.01931	0.04611	-0.01101	43.4
Ammonia	NH <sub>3</sub>	0.24250	0.17031	0.03415	0.19112	4768.7
Argon	A	0.13080	0.02328	0.03931	0	59.9
n-Buthane	C <sub>4</sub> H <sub>10</sub>	1.80319	0.12161	0.24620	0.09423	3500.0
Carbon dioxide	CO <sub>2</sub>	0.50734	0.07132	0.10476	0.07235	660.0
Carbon monoxide	CO	0.13625	0.02617	0.05046	-0.00691	420.0
Ethane	C <sub>2</sub> H <sub>6</sub>	0.59586	0.05861	0.09400	0.01915	900.0
Ethylene	C <sub>2</sub> H <sub>4</sub>	0.62343	0.04964	0.12156	0.03597	226.8
Freon 12	CF <sub>2</sub> Cl <sub>2</sub>	2.40169	0.30500	0.59000	0.62200	0.0
Helium	He	0.00219	0.05984	0.01400	0	0.04
Hydrogen	H <sub>2</sub>	0.02001	-0.00506	0.02096	-0.04359	0.5
Methane	CH <sub>4</sub>	0.23073	0.01855	0.05587	-0.01587	128.3
Methanol	CH <sub>3</sub> OH	3.37543	0.09246	0.60362	0.09928	320.31
Neon	Ne	0.02153	0.02196	0.02060	0	1.01
Nitrogen	N <sub>2</sub>	0.13625	0.02617	0.05046	-0.00691	42.0
Oxygen	O <sub>2</sub>	0.15110	0.02562	0.04624	0.00421	48.0

Table B-3a. Group contributions to molar liquid volume [cm<sup>3</sup>/mol] at the normal boiling point (according to Le Bas)

Carbon	14.8	Fluorine	8.7
Hydrogen	3.7	Chlorine (R-Cl)	21.6
Oxygen		Chlorine (R-CHCl-R)	24.6
double bond	7.4	Bromine	27.0
bound with N, P, S	8.3	Iodine	37.0
in methyl esters and ethers	9.1	Tin	42.3
in ethyl esters and ethers	9.9	Lead	46.5-50.1
in higher esters and ethers	11.0	Mercury	19.0
in acids	12.0	Ring	
Nitrogen		three-membered	-6.0
in primary amines	10.5	four-membered	-8.5
in secondary amines	12.0	five-membered	-11.5
Silicon	32.0	six-membered	-15.0
Phosphor	27.0	naphthalene-ring	-30.0
Sulfur	25.6	anthracene-ring	-47.0

Table B-3b. Molar volumes of liquefied gases at the normal boiling point [cm<sup>3</sup>/mol]

Air	-	29.9	Iodine	I <sub>2</sub>	71.5
Ammonia	NH <sub>3</sub>	25.8	Nitrogen	N <sub>2</sub>	31.2
Bromine	Br <sub>2</sub>	53.2	Nitric oxide	NO	23.6
Carbon dioxide	CO <sub>2</sub>	34.0	Nitrous oxide	N <sub>2</sub> O	36.4
Carbon monoxide	CO	30.7	Oxide	O <sub>2</sub>	25.6
Chlorine	Cl <sub>2</sub>	48.4	Sulfur dioxide	SO <sub>2</sub>	44.8
Hydrogen	H <sub>2</sub>	14.3	Water	H <sub>2</sub> O	18.9
Hydrogen sulfide	H <sub>2</sub> S	32.9			

Table B-4. Reduced liquid density (after Lydersen, Greenkorn, and Hougen)<sup>1</sup>

$T_r$	Saturated liquid				$p_r=1.0$			
	$z_c=0.23$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.23$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$
0.30		3.487	3.287	3.081		3.490	3.290	3.084
0.32		3.450	3.253	3.049		3.454	3.256	3.052
0.34		3.419	3.223	3.021		3.423	3.227	3.025
0.36		3.383	3.189	2.989		3.387	3.193	2.993
0.38		3.348	3.156	2.959		3.354	3.162	2.964
0.40		3.306	3.118	2.922		3.313	3.123	2.928
0.42	3.140	3.271	3.084	2.891	3.181	3.278	3.090	2.897
0.44	3.138	3.234	3.049	2.858	3.174	3.239	3.054	2.863
0.46	3.130	3.195	3.012	2.824	3.164	3.203	3.020	2.831
0.48	3.118	3.156	2.975	2.789	3.149	3.165	2.984	2.797
0.50	3.101	3.115	2.937	2.753	3.132	3.126	2.947	2.763
0.52	3.082	3.076	2.900	2.719	3.115	3.088	2.911	2.729
0.54	3.032	2.996	2.825	2.648	3.071	3.012	2.840	2.662
0.56	3.060	3.036	2.862	2.683	3.099	3.050	2.875	2.696
0.58	3.005	2.956	2.787	2.613	3.040	2.974	2.800	2.630
0.60	2.973	2.913	2.746	2.574	3.007	2.932	2.764	2.591
0.61	2.957	2.893	2.727	2.556	2.989	2.913	2.746	2.574
0.62	2.940	2.868	2.704	2.535	2.965	2.888	2.723	2.553
0.63	2.923	2.849	2.686	2.518	2.954	2.868	2.704	2.535
0.64	2.904	2.825	2.663	2.496	2.938	2.845	2.682	2.514
0.65	2.889	2.800	2.640	2.475	2.919	2.824	2.660	2.494
0.66	2.868	2.781	2.622	2.458	2.900	2.800	2.640	2.475
0.67	2.848	2.757	2.599	2.436	2.882	2.784	2.625	2.461
0.68	2.827	2.733	2.577	2.416	2.864	2.761	2.603	2.400
0.69	2.810	2.709	2.554	2.394	2.846	2.737	2.580	2.419
0.70	2.785	2.686	2.532	2.374	2.828	2.718	2.562	2.402
0.71	2.768	2.661	2.509	2.352	2.805	2.693	2.539	2.380
0.72	2.741	2.637	2.486	2.330	2.782	2.673	2.520	2.362
0.73	2.717	2.614	2.460	2.310	2.759	2.650	2.498	2.342
0.74	2.693	2.586	2.438	2.285	2.736	2.621	2.471	2.316
0.75	2.667	2.557	2.411	2.260	2.714	2.598	2.449	2.296
0.76	2.643	2.534	2.389	2.240	2.690	2.573	2.426	2.274
0.77	2.617	2.505	2.363	2.215	2.668	2.546	2.400	2.250
0.78	2.593	2.478	2.336	2.190	2.664	2.522	2.378	2.229
0.79	2.566	2.450	2.310	2.168	2.621	2.494	2.351	2.204
0.80	2.535	2.420	2.284	2.145	2.597	2.470	2.329	2.183
0.81	2.502	2.390	2.257	2.121	2.577	2.446	2.306	2.160
0.82	2.478	2.359	2.231	2.096	2.553	2.418	2.280	2.137
0.83	2.442	2.327	2.201	2.070	2.526	2.387	2.250	2.109
0.84	2.407	2.295	2.171	2.044	2.498	2.359	2.224	2.085

$T_r$	Saturated liquid				$p_r=1.0$			
	$z_c=0.23$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.23$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$
0.85	2.370	2.263	2.141	2.014	2.468	2.327	2.194	2.057
0.86	2.340	2.227	2.107	1.984	2.436	2.290	2.161	2.038
0.87	2.297	2.191	2.077	1.957	2.402	2.253	2.131	2.002
0.88	2.256	2.155	2.043	1.925	2.364	2.217	2.098	1.972
0.89	2.216	2.116	2.006	1.891	2.324	2.179	2.063	1.941
0.90	2.191	2.076	1.969	1.859	2.285	2.140	2.027	1.911
0.91	2.131	2.032	1.932	1.824	2.232	2.094	1.990	1.877
0.92	2.077	1.989	1.890	1.789	2.174	2.051	1.948	1.843
0.93	2.020	1.940	1.846	1.747	2.113	2.000	1.904	1.802
0.94	1.965	1.888	1.797	1.707	2.057	1.948	1.855	1.762
0.95	1.898	1.829	1.745	1.657	1.994	1.889	1.803	1.713
0.96	1.784	1.765	1.685	1.645	1.920	1.824	1.743	1.661
0.97	1.729	1.689	1.617	1.605	1.850	1.740	1.667	1.594
0.98	1.628	1.598	1.535	1.469	1.748	1.644	1.580	1.513
0.99	1.475	1.470	1.420	1.368	1.624	1.450	1.450	1.397
1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

$T_r$	$p_r=2.0$			$p_r=4.0$			$p_r=6.0$		
	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$
0.30	3.494	3.294	3.088	3.500	3.300	3.094	3.506	3.305	3.098
0.32	3.458	3.260	3.056	3.465	3.267	3.063	3.471	3.272	3.067
0.34	3.427	3.231	3.029	3.437	3.240	3.037	3.442	3.245	3.041
0.36	3.392	3.198	2.988	3.402	3.207	3.006	3.407	3.212	3.011
0.38	3.358	3.170	2.970	3.373	3.180	2.981	3.378	3.185	2.986
0.40	3.322	3.132	2.936	3.334	3.143	2.946	3.339	3.148	2.951
0.42	3.287	3.099	2.905	3.301	3.112	2.917	3.306	3.117	2.922
0.44	3.251	3.065	2.873	3.267	3.080	2.887	3.273	3.086	2.894
0.46	3.215	3.031	2.841	3.232	3.047	2.856	3.239	3.054	2.863
0.48	3.177	2.995	2.808	3.195	3.012	2.824	3.208	3.024	2.835
0.50	3.136	2.957	2.772	3.165	2.975	2.789	3.171	2.990	2.803
0.52	3.099	2.922	2.739	3.120	2.941	2.757	3.140	2.960	2.775
0.54	3.063	2.888	2.707	3.088	2.911	2.729	3.104	2.926	2.743
0.56	3.028	2.855	2.676	3.056	2.881	2.701	3.072	2.896	2.715
0.58	2.990	2.823	2.646	3.020	2.847	2.669	3.040	2.870	2.691
0.60	2.952	2.783	2.609	2.984	2.813	2.637	3.008	2.836	2.659
0.61	2.936	2.768	2.595	2.964	2.794	2.619	2.996	2.825	2.649
0.62	2.916	2.749	2.577	2.945	2.776	2.602	2.980	2.809	2.634
0.63	2.897	2.731	2.560	2.929	2.761	2.588	2.964	2.794	2.620
0.64	2.877	2.712	2.542	2.913	2.746	2.574	2.948	2.779	2.606
0.65	2.852	2.689	2.521	2.893	2.727	2.556	2.932	2.764	2.591
0.66	2.836	2.674	2.507	2.877	2.712	2.542	2.916	2.749	2.577
0.67	2.816	2.655	2.489	2.856	2.693	2.524	2.900	2.734	2.563

## 376 NUMERICAL TABLES

$T_r$	$p_r=2.0$			$p_r=4.0$			$p_r=6.0$		
	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$
0.68	2.797	2.637	2.472	2.836	2.676	2.507	2.881	2.716	2.546
0.69	2.777	2.618	2.454	2.820	2.660	2.494	2.865	2.701	2.532
0.70	2.757	2.599	2.436	2.802	2.642	2.477	2.849	2.686	2.518
0.71	2.733	2.577	2.416	2.784	2.625	2.461	2.833	2.671	2.500
0.72	2.711	2.555	2.395	2.765	2.607	2.444	2.816	2.655	2.489
0.73	2.687	2.533	2.376	2.747	2.590	2.428	2.799	2.639	2.474
0.74	2.662	2.512	2.351	2.729	2.573	2.412	2.781	2.622	2.458
0.75	2.640	2.490	2.333	2.709	2.554	2.394	2.761	2.603	2.441
0.76	2.620	2.473	2.317	2.689	2.535	2.376	2.745	2.588	2.426
0.77	2.594	2.445	2.292	2.672	2.518	2.360	2.729	2.573	2.412
0.78	2.571	2.423	2.271	2.652	2.500	2.344	2.709	2.554	2.394
0.79	2.546	2.400	2.250	2.631	2.480	2.325	2.693	2.539	2.380
0.80	2.524	2.377	2.230	2.609	2.460	2.306	2.673	2.520	2.362
0.81	2.500	2.354	2.206	2.588	2.440	2.287	2.656	2.504	2.347
0.82	2.472	2.330	2.183	2.567	2.420	2.269	2.638	2.487	2.331
0.83	2.447	2.306	2.161	2.546	2.400	2.250	2.619	2.470	2.315
0.84	2.420	2.281	2.137	2.524	2.380	2.232	2.606	2.449	2.295
0.85	2.394	2.256	2.114	2.503	2.360	2.214	2.580	2.433	2.281
0.86	2.358	2.231	2.098	2.482	2.340	2.195	2.562	2.416	2.265
0.87	2.330	2.204	2.070	2.461	2.320	2.176	2.543	2.398	2.248
0.88	2.302	2.177	2.049	2.438	2.299	2.156	2.524	2.380	2.232
0.89	2.274	2.150	2.022	2.415	2.277	2.136	2.505	2.362	2.216
0.90	2.243	2.122	1.998	2.390	2.257	2.119	2.486	2.344	2.200
0.91	2.211	2.092	1.970	2.365	2.235	2.100	2.466	2.325	2.182
0.92	2.180	2.064	1.943	2.342	2.214	2.080	2.440	2.307	2.165
0.93	2.145	2.033	1.913	2.316	2.191	2.060	2.420	2.288	2.147
0.94	2.104	2.001	1.887	2.292	2.168	2.039	2.400	2.268	2.129
0.95	2.063	1.965	1.856	2.267	2.145	2.018	2.378	2.249	2.113
0.96	2.028	1.931	1.825	2.240	2.120	1.995	2.356	2.229	2.096
0.97	1.988	1.892	1.790	2.211	2.095	1.973	2.334	2.208	2.077
0.98	1.946	1.852	1.755	2.184	2.072	1.950	2.313	2.188	2.059
0.99	1.902	1.810	1.719	2.155	2.043	1.925	2.289	2.165	2.038
1.00	1.854	1.764	1.676	2.127	2.016	1.900	2.266	2.143	2.018

$T_r$	$p_r=10$			$p_r=15$			$p_r=20$		
	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$
0.30	3.512	3.320	3.112	3.527	3.325	3.116	3.535	3.333	3.124
0.32	3.484	3.285	3.079	3.495	3.295	3.088	3.506	3.305	3.098
0.34	3.453	3.255	3.051	3.463	3.265	3.060	3.474	3.275	3.070
0.36	3.421	3.225	3.028	3.431	2.235	3.032	3.442	3.245	3.042
0.38	3.389	3.195	2.995	3.401	3.206	3.005	3.410	3.215	3.013
0.40	3.357	3.165	2.967	3.370	3.177	2.978	3.378	3.185	2.985

$T_r$	$p_r=10$			$p_r=15$			$p_r=20$		
	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$
0.42	3.325	3.135	2.938	3.340	3.147	2.950	3.350	3.158	2.960
0.44	3.292	3.104	2.909	3.307	3.118	2.923	3.319	3.129	2.933
0.46	3.262	3.075	2.882	3.278	3.090	2.896	3.288	3.100	2.906
0.48	3.230	3.045	2.854	3.242	3.068	2.876	3.257	3.071	2.878
0.50	3.198	3.015	2.826	3.214	3.030	2.840	3.226	3.041	2.850
0.52	3.166	2.985	2.798	3.182	3.000	2.812	3.197	3.014	2.825
0.54	3.134	2.955	2.770	3.153	2.973	2.787	3.167	2.986	2.799
0.56	3.103	2.925	2.742	3.120	2.949	2.764	3.139	2.959	2.773
0.58	3.072	2.896	2.714	3.093	2.916	2.733	3.109	2.931	2.750
0.60	3.044	2.870	2.690	3.063	2.888	2.707	3.081	2.905	2.723
0.61	3.028	2.855	2.676	3.050	2.875	2.695	3.070	2.894	2.713
0.62	3.013	2.841	2.663	3.036	2.862	2.683	3.056	2.881	2.700
0.63	2.998	2.828	2.651	3.022	2.849	2.670	3.044	2.870	2.690
0.64	2.985	2.814	2.638	3.008	2.836	2.660	3.031	2.858	2.679
0.65	2.970	2.800	2.624	2.995	2.824	2.647	3.018	2.845	2.667
0.66	2.951	2.782	2.602	2.982	2.811	2.635	3.005	2.833	2.655
0.67	2.940	2.772	2.598	2.968	2.798	2.623	2.991	2.820	2.643
0.68	2.918	2.751	2.579	2.954	2.785	2.610	2.980	2.809	2.633
0.69	2.910	2.743	2.571	2.940	2.776	2.602	2.967	2.797	2.622
0.70	2.890	2.730	2.560	2.928	2.760	2.586	2.955	2.786	2.613
0.71	2.872	2.716	2.547	2.915	2.748	2.577	2.943	2.775	2.600
0.72	2.860	2.701	2.533	2.901	2.735	2.565	2.931	2.763	2.591
0.73	2.851	2.688	2.521	2.894	2.720	2.559	2.917	2.750	2.579
0.74	2.837	2.675	2.509	2.874	2.710	2.542	2.906	2.740	2.570
0.75	2.812	2.661	2.495	2.861	2.697	2.530	2.896	2.730	2.560
0.76	2.800	2.646	2.480	2.848	2.685	2.518	2.886	2.721	2.552
0.77	2.784	2.631	2.468	2.833	2.671	2.505	2.870	2.706	2.538
0.78	2.770	2.617	2.454	2.820	2.659	2.494	2.859	2.695	2.528
0.79	2.750	2.602	2.440	2.807	2.646	2.482	2.847	2.684	2.517
0.80	2.735	2.587	2.432	2.790	2.634	2.476	2.830	2.673	2.513
0.81	2.719	2.572	2.418	2.778	2.621	2.464	2.820	2.661	2.501
0.82	2.704	2.558	2.405	2.762	2.609	2.452	2.810	2.650	2.490
0.83	2.687	2.542	2.389	2.750	2.595	2.439	2.792	2.639	2.481
0.84	2.671	2.527	2.375	2.740	2.583	2.428	2.784	2.628	2.470
0.85	2.655	2.512	2.361	2.720	2.571	2.417	2.772	2.616	2.459
0.86	2.639	2.496	2.346	2.708	2.559	2.405	2.762	2.605	2.449
0.87	2.621	2.479	2.330	2.698	2.545	2.392	2.752	2.595	2.439
0.88	2.606	2.465	2.317	2.682	2.532	2.380	2.740	2.585	2.430
0.89	2.590	2.450	2.303	2.670	2.519	2.368	2.730	2.574	2.420
0.90	2.572	2.434	2.282	2.658	2.506	2.349	2.719	2.563	2.403
0.91	2.560	2.418	2.267	2.644	2.493	2.340	2.707	2.552	2.392
0.92	2.540	2.402	2.252	2.632	2.481	2.330	2.695	2.541	2.382

$T_r$	$p_r=10$			$p_r=15$			$p_r=20$		
	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$
0.93	2.532	2.387	2.238	2.620	2.470	2.316	2.685	2.531	2.373
0.94	2.514	2.370	2.222	2.606	2.457	2.303	2.674	2.521	2.363
0.95	2.498	2.355	2.208	2.592	2.445	2.292	2.663	2.511	2.354
0.96	2.480	2.338	2.192	2.581	2.433	2.281	2.652	2.500	2.344
0.93	2.532	2.387	2.238	2.620	2.470	2.316	2.685	2.531	2.373
0.94	2.514	2.370	2.222	2.606	2.457	2.303	2.674	2.521	2.363
0.95	2.498	2.355	2.208	2.592	2.445	2.292	2.663	2.511	2.354
0.96	2.480	2.338	2.192	2.581	2.433	2.281	2.652	2.500	2.344
0.97	2.463	2.322	2.177	2.567	2.420	2.269	2.640	2.489	2.333
0.98	2.446	2.306	2.162	2.555	2.409	2.258	2.628	2.480	2.323
0.99	2.429	2.290	2.147	2.541	2.396	2.246	2.617	2.467	2.313
1.00	2.412	2.274	2.132	2.532	2.383	2.234	2.606	2.457	2.303

$T_r$	$p_r=25$			$p_r=30$		
	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$
0.30	3.540	3.337	3.128	3.546	3.343	3/133
0.32	3.511	3.310	3.102	3.517	3.316	3.108
0.34	3.481	3.282	3.076	3.489	3.289	3.083
0.36	3.453	3.255	3.051	3.459	3.261	3.057
0.38	3.421	3.225	3.023	3.430	3.233	3.030
0.40	3.390	3.196	2.996	3.400	3.205	3.004
0.42	3.360	3.168	2.969	3.370	3.177	2.978
0.44	3.306	3.140	2.943	3.341	3.150	2.952
0.46	3.302	3.113	2.918	3.310	3.121	2.925
0.48	3.274	3.085	3.892	3.282	3.094	2.900
0.50	3.245	3.059	3.867	3.252	3.066	2.874
0.52	3.214	3.030	2.840	3.225	3.040	2.849
0.54	3.186	3.004	2.816	3.198	3.015	2.826
0.56	3.157	2.956	2.789	3.170	2.989	2.802
0.58	3.130	2.951	2.766	3.145	2.965	2.779
0.60	3.103	2.925	2.742	3.120	2.941	2.757
0.61	3.090	2.913	2.730	3.108	2.930	2.746
0.62	3.076	2.900	2.718	3.096	2.919	2.736
0.63	3.064	2.889	2.708	3.082	2.906	2.724
0.64	3.052	2.877	2.697	3.065	2.890	2.709
0.65	3.040	2.866	2.686	3.060	2.885	2.704
0.66	3.028	2.855	2.676	3.050	2.875	2.695
0.67	3.016	2.843	2.665	3.038	2.864	2.684
0.68	3.004	2.832	2.654	3.027	2.854	2.675
0.69	2.992	2.820	2.643	3.016	2.843	2.665
0.70	2.981	2.810	2.635	3.005	2.833	2.57
0.71	2.969	2.799	2.625	2.994	2.823	2.648

$T_r$	$p_r=25$			$p_r=30$		
	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$	$z_c=0.25$	$z_c=0.27$	$z_c=0.29$
0.72	2.956	2.787	2.614	2.985	2.814	2.639
0.73	2.945	2.776	2.604	2.974	2.804	2.630
0.74	2.933	2.765	2.593	2.964	2.794	2.620
0.75	2.921	2.754	2.583	2.953	2.784	2.610
0.76	2.911	2.744	2.574	2.942	2.774	2.602
0.77	2.899	2.733	2.563	2.932	2.764	2.592
0.78	2.887	2.722	2.553	2.920	2.753	2.582
0.79	2.877	2.712	2.544	2.910	2.743	2.578
0.80	2.864	2.702	2.540	2.900	2.734	2.570
0.81	2.852	2.693	2.531	2.890	2.725	2.561
0.82	2.844	2.683	2.522	2.880	2.715	2.552
0.83	2.832	2.673	2.513	2.870	2.706	2.544
0.84	2.820	2.664	2.504	2.860	2.698	2.536
0.85	2.810	2.655	2.496	2.852	2.689	2.528
0.86	2.800	2.645	2.486	2.840	2.680	2.519
0.87	2.792	2.635	2.477	2.829	2.672	2.512
0.88	2.780	2.626	2.468	2.821	2.669	2.509
0.89	2.770	2.616	2.459	2.816	2.655	2.496
0.90	2.760	2.608	2.445	2.808	2.647	2.482
0.91	2.756	2.598	2.435	2.798	2.638	2.473
0.92	2.745	2.588	2.426	2.790	2.630	2.466
0.93	2.736	2.579	2.418	2.781	2.622	2.458
0.94	2.726	2.570	2.409	2.773	2.614	2.451
0.95	2.717	2.561	2.400	2.763	2.605	2.442
0.96	2.706	2.551	2.391	2.753	2.596	2.434
0.97	2.696	2.542	2.383	2.745	2.588	2.426
0.98	2.686	2.532	2.373	2.736	2.580	2.419
0.99	2.676	2.523	2.365	2.727	2.571	2.410
1.00	2.667	2.514	2.357	2.720	2.563	2.403

<sup>1</sup> Reid R. C., and Sherwood T. K., *The Properties of Gases and Liquids*, McGraw-Hill, New York, 1958.

Table B-5. Coefficients in the equation  $C_p^* = a + bT + cT^2 + dT^3$  [J/mol·K] for gases  
(inorganic substances)<sup>1</sup>

Gas		$a$	$b \cdot 10^3$	$c \cdot 10^6$	$d \cdot 10^9$	Recommended range of temperatures [K]
Air	-	26.74	7.377	-1.112	-	273-1500
Ammonia	NH <sub>3</sub>	27.57	25.64	9.907	-6.691	273-1500
Carbon dioxide	CO <sub>2</sub>	22.26	59.81	-35.01	7.469	273-1800
Carbon monoxide	CO	28.16	1.675	5.372	-2.222	273-1800
Chlorine	Cl <sub>2</sub>	28.56	23.90	-21.38	6.477	273-1500
Deuterium	D <sub>2</sub>	28.60	0.879	1.959	-	298-1500
Fluorine	F <sub>2</sub>	25.60	24.55	-17.53	4.102	273-2000
Hydrogen iodide	HI	30.09	9.937	-	-	
Hydrogen	H <sub>2</sub>	29.11	-1.916	4.004	0.8704	273-1800
Hydrogen chloride	HCl	28.19	1.805	1.513	-	273-1500
Hydrogen sulfide	H <sub>2</sub> S	29.60	13.10	5.711	-3.294	273-1800
Hydrogen fluoride	HF	26.92	3.433	-	-	273-2000
Nitric oxide	NO	27.05	9.872	-3.226	0.3655	273-3800
Nitrogen	N <sub>2</sub>	28.90	-1.571	8.081	-2.873	273-1800
Nitrogen dioxide	NO <sub>2</sub>	22.94	57.15	-35.21	7.871	273-1500
Nitrogen tetraoxide	N <sub>2</sub> O <sub>4</sub>	33.08	186.7	-113.5	-	273- 600
Nitrous oxide	N <sub>2</sub> O	24.11	58.63	-35.62	10.58	273-1500
Oxygen	O <sub>2</sub>	25.61	13.26	-4.208	-	273-1500
Phosfine	PH <sub>3</sub>	18.82	60.17	170.5	-	298-1500
Phosphor pentachloride	PCl <sub>5</sub>	19.84	449.4	-499.1	-	298- 500
Steam	H <sub>2</sub> O	32.24	1.923	10.55	-3.595	273-1800
Sulfur dioxide	SO <sub>2</sub>	25.78	57.95	-38.11	8.612	173-1800
Sulfur trioxide	SO <sub>3</sub>	31.21	80.09	-27.75	-	173-1500
Sulfuryl chloride	SO <sub>2</sub> Cl <sub>2</sub>	53.76	79.55	-	-	298- 500

<sup>1</sup> After Hougen O. A., and Watson K. M., *Chemical Process Principles*, John Wiley, New York, 1947 (by permission).

Table B-6. Coefficients in the equation  $C_p^* = a + bT + cT^2 + dT^3$  [J/mol·K] for gases (organic substances)<sup>1</sup>

Gas		<i>a</i>	<i>b</i> ·10 <sup>3</sup>	<i>c</i> ·10 <sup>6</sup>	<i>d</i> ·10 <sup>9</sup>	Recommended range of temperatures [K]
Acetaldehyde	CH <sub>3</sub> CHO	17.54	132.5	-21.56	-15.91	273-1000
Acetic acid	CH <sub>3</sub> COOH	21.77	193.3	-76.83	-	300- 700
Acetone	(CH <sub>3</sub> ) <sub>2</sub> CO	6.804	278.9	-156.5	34.78	273-1500
Acetylene	C <sub>2</sub> H <sub>2</sub>	21.81	92.11	-65.27	18.21	273-1500
Benzene	C <sub>6</sub> H <sub>6</sub>	-36.22	484.7	-315.7	77.62	273-1500
i-Buthane	C <sub>4</sub> H <sub>10</sub>	-7.913	416.0	-230.1	49.91	273-1500
n-Buthane	C <sub>4</sub> H <sub>10</sub>	3.957	371.5	-183.4	35.00	273-1500
Chloroform	CHCl <sub>3</sub>	31.86	144.9	-111.7	30.75	273-1500
Cyclohexane	C <sub>6</sub> H <sub>12</sub>	-66.72	688.9	-385.3	80.68	273-1500
Ethane	C <sub>2</sub> H <sub>6</sub>	6.900	172.7	-64.06	7.285	273-1500
Ethanol	C <sub>2</sub> H <sub>5</sub> OH	19.89	209.6	-103.8	20.05	273-1000
Ethylbenzene	C <sub>8</sub> H <sub>10</sub>	-35.16	667.2	-418.8	100.3	273-1500
Ethylene	C <sub>2</sub> H <sub>4</sub>	3.952	156.4	-83.44	17.67	273-1500
Formaldehyde	HCHO	22.81	40.78	7.13	-8.700	273-1500
Formic acid	HCOOH	30.69	89.26	-34.56	-	300- 700
n-Heptane	C <sub>7</sub> H <sub>16</sub>	22.61	570.6	-204.2	-	298-1500
n-Hexane	C <sub>6</sub> H <sub>14</sub>	6.938	522.2	-286.5	57.69	273-1500
Methane	CH <sub>4</sub>	19.89	50.24	12.69	-11.01	273-1500
Methanol	CH <sub>3</sub> OH	19.05	91.52	-12.18	-8.039	273-1000
Methylacetylene	C <sub>3</sub> H <sub>4</sub>	18.46	157.5	60.21	-	
Methylchloride	CH <sub>3</sub> Cl	14.91	96.29	-31.57	-	273- 773
Methyldichloride	CH <sub>2</sub> Cl <sub>2</sub>	17.58	143.1	-98.39	25.41	273-1500
Methyliodide	CH <sub>3</sub> I	17.19	102.5	-40.75	-	298- 600
n-Octane	C <sub>8</sub> H <sub>18</sub>	0.967	652.9	-233.9	-	298-1500
n-Pentane	C <sub>5</sub> H <sub>12</sub>	20.49	377.3	-117.4	-	273-1500
Propane	C <sub>3</sub> H <sub>8</sub>	-4.044	304.8	-157.2	31.74	273-1500
Propanol	C <sub>3</sub> H <sub>7</sub> OH	-2.596	312.6	105.6	-	
Propylene	C <sub>3</sub> H <sub>6</sub>	3.153	238.3	-121.8	24.62	273-1500
Styrene	C <sub>8</sub> H <sub>8</sub>	-24.99	601.0	-383.1	92.24	273-1500
Toluene	C <sub>7</sub> H <sub>8</sub>	-34.39	559.2	-344.6	80.39	273-1500
m-Xylene	C <sub>8</sub> H <sub>10</sub>	8.189	458.3	-149.0	-	298-1500
o-Xylene	C <sub>8</sub> H <sub>10</sub>	19.27	437.4	-140.7	-	298-1500
p-Xylene	C <sub>8</sub> H <sub>10</sub>	7.729	454.7	-147.4	-	298-1500

<sup>1</sup> After Hougen O. A., and Watson K. M., *Chemical Process Principles*, John Wiley, New York, 1947 (by permission).

Table B-7. Force parameters in the Lennard-Jones potential equation (based on viscosities)<sup>1</sup>

Substance	$\epsilon/k$ [K]	$\sigma \cdot 10^{10}$ [m]	Substance	$\epsilon/k$ [K]	$\sigma \cdot 10^{10}$ [m]
A	124	3.418	CH <sub>4</sub>	137	3.882
Air	97	3.617	C <sub>2</sub> H <sub>2</sub>	185	4.221
AsH <sub>3</sub>	281	4.060	C <sub>2</sub> H <sub>4</sub>	205	4.232
Br <sub>2</sub>	520	4.268	C <sub>2</sub> H <sub>6</sub>	230	4.418
Cl <sub>2</sub>	357	4.115	C <sub>3</sub> H <sub>8</sub>	254	5.061
CCl <sub>4</sub>	327	5.881	n-C <sub>4</sub> H <sub>10</sub>	410	4.997
D <sub>2</sub>	39.3	2.948	i-C <sub>4</sub> H <sub>10</sub>	313	5.341
F <sub>2</sub>	112	3.653	n-C <sub>5</sub> H <sub>12</sub>	345	5.769
H <sub>2</sub>	38	2.915	n-C <sub>6</sub> H <sub>14</sub>	413	5.909
HCl	360	3.305	n-C <sub>8</sub> H <sub>18</sub>	320	7.451
HII	324	4.123	n-C <sub>9</sub> H <sub>20</sub>	240	8.448
He	10.22	2.576	Cyclohexane	324	6.093
Hg	851	2.898	C <sub>6</sub> H <sub>6</sub>	440	5.270
I <sub>2</sub>	550	4.982	CH <sub>3</sub> OH	507	3.585
Kr	190	3.610	C <sub>2</sub> H <sub>5</sub> OH	391	4.455
N <sub>2</sub>	79.8	3.749	CH <sub>3</sub> Cl	855	3.375
NO	91.0	3.599	CH <sub>2</sub> Cl <sub>2</sub>	406	4.759
N <sub>2</sub> O	237	3.816	CHCl <sub>3</sub>	327	5.430
Ne	27.5	2.858	CO	110	3.590
O <sub>2</sub>	88.0	3.541	CO <sub>2</sub>	190	3.996
SO <sub>2</sub>	252	4.290	COS	335	4.130
SnCl <sub>4</sub>	1550	4.540	CS <sub>2</sub>	488	4.438
Xe	229	4.055	C <sub>2</sub> N <sub>2</sub>	339	4.380

<sup>1</sup> Reid R. C., and Sherwood T. K., *The Properties of Gases and Liquids*, McGraw-Hill, New York, 1958 (by permission).

Table B-8. Functions in determination of nonpolar gas properties<sup>1</sup>

$T^*$	$\Omega_{u\lambda}$	$\Omega_D$	$T^*$	$\Omega_{u\lambda}$	$\Omega_D$	$T^*$	$\Omega_{u\lambda}$	$\Omega_D$
0.30	2.785	2.662	1.65	1.264	1.153	4.00	0.9700	0.8836
0.35	2.628	2.476	1.70	1.248	1.140	4.10	0.9649	0.8788
0.40	2.492	2.318	1.75	1.234	1.128	4.20	0.9600	0.8740
0.45	2.368	2.184	1.80	1.221	1.116	4.30	0.9553	0.8694
0.50	2.257	2.066	1.85	1.209	1.105	4.40	0.9507	0.8652
0.55	2.156	1.966	1.90	1.197	1.094	4.50	0.9464	0.8610
0.60	2.065	1.877	1.95	1.186	1.084	4.60	0.9422	0.8568
0.65	1.982	1.798	2.00	1.175	1.075	4.70	0.9382	0.8530
0.70	1.908	1.729	2.10	1.156	1.057	4.80	0.9343	0.8492
0.75	1.841	1.667	2.20	1.138	1.041	4.90	0.9305	0.8456
0.80	1.780	1.612	2.30	1.122	1.026	5.0	0.9269	0.8422
0.85	1.725	1.562	2.40	1.107	1.012	6.0	0.8963	0.8124
0.90	1.675	1.517	2.50	1.093	0.9996	7.0	0.8727	0.7896
0.95	1.629	1.476	2.60	1.081	0.9878	8.0	0.8538	0.7712
1.00	1.587	1.439	2.70	1.069	0.9770	9.0	0.8379	0.7556
1.05	1.549	1.406	2.80	1.058	0.9672	10	0.8242	0.7424
1.10	1.514	1.375	2.90	1.048	0.9576	20	0.7432	0.6640
1.15	1.482	1.346	3.00	1.039	0.9490	30	0.7005	0.6232
1.20	1.452	1.320	3.10	1.030	0.9406	40	0.6718	0.5960
1.25	1.424	1.296	3.20	1.022	0.9328	50	0.6504	0.5756
1.30	1.399	1.273	3.30	1.014	0.9256	60	0.6335	0.5596
1.35	1.375	1.253	3.40	1.007	0.9186	70	0.6194	0.5464
1.40	1.353	1.233	3.50	0.9999	0.9120	80	0.6076	0.5352
1.45	1.333	1.215	3.60	0.9932	0.9058	90	0.5973	0.5256
1.50	1.314	1.198	3.70	0.9870	0.8998	100	0.5882	0.5170
1.55	1.296	1.182	3.80	0.9811	0.8942	200	0.5320	0.4644
1.60	1.279	1.167	3.90	0.9755	0.8888	400	0.4811	0.4170

<sup>1</sup> Bird R. B., Hirschfelder J. O., and Curtiss C. F., *Molecular Theory of Gases and Liquids*, John Wiley, New York, 1954; *Trans. Am. Soc. Mech. Engrs*, 76, 1011, 1954 (by permission).

Table B-9. Values of the function  $f_1(T^*)$  in gas viscosity determination by the Bromley and Wilke method<sup>1</sup>

$T^*$	$f_1$	$T^*$	$f_1$	$T^*$	$f_1$
0.30	0.1969	1.65	1.0174	4.0	2.0719
0.35	0.2252	1.70	1.0453	4.1	2.1090
0.40	0.2540	1.75	1.0729	4.2	2.1457
0.45	0.2834	1.80	1.0999	4.3	2.1820
0.50	0.3134	1.85	1.1264	4.4	2.2180
0.55	0.3440	1.90	1.1529	4.5	2.2536
0.60	0.3751	1.95	1.1790	4.6	2.2888
0.65	0.4066	2.00	1.2048	4.7	2.3237
0.70	0.4384	2.1	1.2558	4.8	2.3583
0.75	0.4704	2.2	1.3057	4.9	2.3926
0.80	0.5025	2.3	1.3547	5.0	2.4264
0.85	0.5346	2.4	1.4028	6.0	2.751
0.90	0.5666	2.5	1.4501	7.0	3.053
0.95	0.5985	2.6	1.4962	8.0	3.337
1.00	0.6302	2.7	1.5417	9.0	3.607
1.05	0.6616	2.8	1.5861	10	3.866
1.10	0.6928	2.9	1.6298	20	6.063
1.15	0.7237	3.0	1.6728	30	7.880
1.20	0.7544	3.1	1.7154	40	9.488
1.25	0.7849	3.2	1.7573	50	10.958
1.30	0.8151	3.3	1.7983	60	12.324
1.35	0.8449	3.4	1.8388	70	13.615
1.40	0.8744	3.5	1.8789	80	14.839
1.45	0.9036	3.6	1.9186	90	16.010
1.50	0.9325	3.7	1.9576	100	17.137
1.55	0.9611	3.8	1.9962	200	26.80
1.60	0.9894	3.9	2.0343	400	41.90

<sup>1</sup> Bromley L. A., and Wilke C. R., *Ind. Eng. Chem.*, 43, 1641, 1951 (by permission).

Table B-10. Correction factors for viscosity,  $\mu$ , thermal conductivity,  $\lambda$ , and diffusivity,  $D$ , of nonpolar gases<sup>1</sup>

$T^*$	$f_{\mu}$	$f_{\lambda}$	$f_D$
0.30	1.0014	1.0022	1.0001
0.50	1.0002	1.0003	1.0000
0.75	1.0000	1.0000	1.0000
1.00	1.0000	1.0001	1.0000
1.25	1.0001	1.0002	1.0002
1.50	1.0004	1.0006	1.0006
2.00	1.0014	1.0021	1.0016
2.50	1.0025	1.0038	1.0026
3.00	1.0034	1.0052	1.0037
4.00	1.0049	1.0076	1.0050
5.00	1.0058	1.0090	1.0059
10.0	1.0075	1.0116	1.0076
50.0	1.0079	1.0124	1.0080
100	1.0080	1.0125	1.0080
400	1.0080	1.0125	1.0080

<sup>1</sup> Bird R. B., Hirschfelder J. O., and Curtiss C. F., *Molecular Theory of Gases and Liquids*, John Wiley, New York, 1954; *Trans. Am. Soc. Mech. Engrs.*, 76, 1011, 1954 (by permission).

Table B-11. The Sutherland constants for some gases and vapors  
(within the range 0-250°C)

Substance	$S$ [K]	Substance	$S$ [K]	Substance	$S$ [K]
Acetone	541	Ethyl chloride	411	Methyl chloride	454
Acetylene	215	Ethyl ether	404	Methyl dichloride	395
Air	112	Ethylene	241	Methyl ether	425
Ammonia	142	Helium	80	Neon	56
Argon	503	n-Hexane	436.1	Nitric oxide	128
Benzene	447.5	Hydrogen	84.4	Nitrogen	104
Bromine	533	Hydrogen bromide	357	Nitrous oxide	260
Buthane	358	Hydrogen chloride	362	Oxygen	125
i-Buthane	330	Hydrogen cyanide	330	n-Pentane	383
Carbon dioxide	254	Hydrogen iodide	331	Propane	278
Carbon disulfide	499.5	Hydrogen sulfide	331	i-Propanol	459.9
Carbon monoxide	101.2	Iodine	568	n-Propanol	515.6
Carbon tetrachloride	365	Krypton	188	Propylene	362
Chlorine	330	Methane	164	Sulfur dioxide	416
Chloroform	373	Methanol	487	Water (steam)	650
Ethane	252	Methyl bromide	402	Xenon	252
Ethanol	407				

<sup>1</sup> Partington J., *An Advanced Treatise on Physical Chemistry*, Longman, London, 1949 (by permission).

Table B-12. Values of the function  $\lambda_r/\mu_r = f(T_r)$  (low pressure)<sup>1</sup>

$T_r$	0.4	0.5	1.0	1.4	2.0	3.0	5.0	10	40
$\lambda_r/\mu_r$	0.565	0.655	0.855	0.931	0.970	1.018	1.110	1.192	1.395

<sup>1</sup> Gamson B. W., *Chem. Eng. Progr.*, 45, 154, 1949 (by permission).

Table B-13. Correction factors,  $\beta$ , and solubility parameters,  $\delta$ , in determination of absorption equilibrium according to the method of Hildebrand<sup>1</sup>

Solvent \ Gas	Values of the correction factors, $\beta$ , $t=25^\circ\text{C}$ , $p \approx 0.1 \text{ MPa}$								$\delta \cdot 10^{-3}$	$\mu \cdot 10^{30}$
	H <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	A	CO	CH <sub>4</sub>	C <sub>2</sub> H <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>	(J/mol <sup>3</sup> ) <sup>1/2</sup>	C·m
Acetone	3.46	1.69	1.43	1.77	1.7	1.57	0.286	2.03	-	(20.2)
Aniline	7.48	8.30	-	-	6.40	-	-	-	-	5.0
Benzene	3.065	2.27	1.62	1.81	2.0	1.69	1.18	1.3	1.66	18.7
Carbon tetrachloride	2.45	1.56	1.10	-	1.44	1.22	1.87	1.03	1.17	17.7
Carbon disulfide	8.70	6.90	-	-	6.21	-	-	-	-	20.5
Chlorobenzene	3.01	2.32	1.67	-	2.025	1.68	1.39	1.26	1.69	19.4
Chloroform	3.64	2.25	1.79	-	1.98	-	-	-	-	3.7
Cyclohexane	2.105	1.385	-	1.08	-	1.24	-	-	-	16.8
Ethyl ether	1.45	0.799	0.667	-	0.757	0.773	-	-	-	3.7
n-Hexane	1.23	0.800	0.684	-	-	0.89	-	0.944	1.41	14.9
Methanol	5.095	4.255	4.15	3.60	3.94	4.93	-	-	-	(29.5)
Methyl acetate	2.61	1.675	1.45	-	1.48	1.75	0.295	1.30	-	(19.3)
Nitrobenzene	5.13	3.80	-	-	3.25	-	-	-	2.315	20.5
Water	53.3	83.3	57.4	64.0	71.10	146	27.6	173	758	47
m-Xylene	1.94	1.63	-	-	1.40	1.36	-	-	-	18.0
Extrapolated values of vapor pressure [MPa]	126.7	101.3	76.7	63.3	79.1	29.3	4.87	6.67	4.05	

<sup>1</sup> After Ciborowski J., Pohorecki R., *Przem. Chem.*, 39, 762, 1960.

Table B-14. Partial molar volumes of dissolved gases at 25°C [cm<sup>3</sup>/mol]<sup>1</sup>

Solvent \ Gas	H <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	CO	CO <sub>2</sub>	SO <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>
	Acetone	38	55	48	53	-	68	55	49	58
Benzene	36	53	46	52	-	48	52	51	61	67
Carbon tetrachloride	38	53	45	53	-	54	52	54	61	67
Chlorobenzene	34	50	43	46	-	48	49	50	58	64
Ethyl ether	50	66	56	62	-	-	58	-	-	-
Methanol	35	52	45	51	43	-	52	-	-	-
Methyl acetate	38	54	48	53	-	47	53	49	62	69
Water	26	40	31	36	33	-	37	-	-	-

<sup>1</sup> After Ciborowski J., Pohorecki R., *Przem. Chem.*, 39, 762, 1960.

Table B-15a. Partial molar volumes of dissolved gases at different temperatures [cm<sup>3</sup>/mol]<sup>1</sup>

Gas Solvent	H <sub>2</sub> H <sub>2</sub> O	H <sub>2</sub> O	N <sub>2</sub> CH <sub>3</sub> OH	CO <sub>2</sub> H <sub>2</sub> O	CH <sub>4</sub> H <sub>2</sub> O
0°C	24	41	47	32	36
25°C	26	40	52	33	37
50°C	24	38	54	33	38

<sup>1</sup> After Ciborowski J., Pohorecki R., *Przem. Chem.*, 39, 762, 1960.

Table B-15b. Apparent partial molar volumes of dissolved gases at different temperatures [cm<sup>3</sup>/mol]<sup>1</sup>

Gas Solvent	H <sub>2</sub> H <sub>2</sub> O	H <sub>2</sub> O	N <sub>2</sub> CH <sub>3</sub> OH	CO <sub>2</sub> H <sub>2</sub> O	CH <sub>4</sub> H <sub>2</sub> O
0°C	20.0	-	18.8	29.0	-
25°C	19.5	32.8	23.2	29.0	50.0
50°C	19.6	33.4	27.5	29.0	44.2

<sup>1</sup> After Ciborowski J., Pohorecki R., *Przem. Chem.*, 39, 762, 1960.

Table B-16. Contribution of ions and solutes in determination of the Henry's constant; *h* [cm<sup>3</sup>/mol]

(a) According to Barrett<sup>1</sup>

<i>h</i> <sub>+</sub>		<i>h</i> <sub>-</sub>		<i>h<sub>g</sub></i> (15°C)		<i>h<sub>g</sub></i> (25°C)		<i>h<sub>g</sub></i> (CO <sub>2</sub> )	<i>t</i> (°C)	<i>h<sub>g</sub></i>
H <sup>+</sup>	0	OH <sup>-</sup>	66	H <sub>2</sub>	-8	H <sub>2</sub>	-2	0.2	7	
Na <sup>+</sup>	91	Cl <sup>-</sup>	21	O <sub>2</sub>	34	O <sub>2</sub>	22	15	-10	
K <sup>+</sup>	74	Br <sup>-</sup>	12	CO <sub>2</sub>	10	CO <sub>2</sub>	-19	25	-19	
NH <sub>4</sub> <sup>+</sup>	28	OCl <sup>-</sup>	(16)	N <sub>2</sub> O	3	N <sub>2</sub> O	0	40	-26	
Mg <sup>2+</sup>	51	NO <sub>3</sub> <sup>-</sup>	-1			H <sub>2</sub> S	-33	50	(-29)	
Zn <sup>2+</sup>	48	HCO <sub>3</sub> <sup>-</sup>	(12)			NH <sub>3</sub>	-54	60	(-16)	
Ca <sup>2+</sup>	53	CO <sub>3</sub> <sup>2-</sup>	(21)			C <sub>2</sub> H <sub>2</sub>	-9			
		SO <sub>4</sub> <sup>2-</sup>	22			SO <sub>2</sub>	-103			

(b) According to van Krevelen and Hofstijzer<sup>2</sup>

<i>h</i> <sub>+</sub>		<i>h</i> <sub>-</sub>		<i>h<sub>g</sub></i> (15°C)		<i>h<sub>g</sub></i> (25°C)	
H <sup>+</sup>	0	OH <sup>-</sup>	61	H <sub>2</sub>	2	H <sub>2</sub>	-1
Na <sup>+</sup>	94	Cl <sup>-</sup>	21	O <sub>2</sub>	33	O <sub>2</sub>	19
K <sup>+</sup>	71	Br <sup>-</sup>	11	CO <sub>2</sub>	-10	CO <sub>2</sub>	-17
NH <sub>4</sub> <sup>+</sup>	31	I <sup>-</sup>	5	N <sub>2</sub> O	6	N <sub>2</sub> O	1

Mg <sup>2+</sup>	46	NO <sub>3</sub> <sup>-</sup>	0			H <sub>2</sub> S	-39
Zn <sup>2+</sup>	46	CO <sub>3</sub> <sup>2-</sup>	(21)			NH <sub>3</sub>	-50
Ca <sup>2+</sup>	51	SO <sub>4</sub> <sup>2-</sup>	21			C <sub>2</sub> H <sub>2</sub>	-11
Ba <sup>2+</sup>	(60)					SO <sub>2</sub>	-105
Mn <sup>2+</sup>	(46)						
Fe <sup>2+</sup>	(49)						
Co <sup>2+</sup>	(58)						
Ni <sup>2+</sup>	(59)						

<sup>1</sup> After P. V. L. Barrett, Ph. D. Thesis, University of Cambridge, Cambridge, 1966.

<sup>2</sup> After van Krevelen D. W., and Hofstijzer P. J., XXI Congrès Int. de Chimie Industrielle, Chim. Ind., 168, 1948.

Table B-17. Values of functions  $\Phi$ ,  $\Phi'$ , and  $\Phi''$  in the solution due to Blasius  
for flow along a flat, thin plate<sup>1</sup>

$\eta$	$\Phi$	$\Phi'$	$\Phi''$
0.0	0.00000	0.00000	0.33206
0.2	0.00664	0.06641	0.33199
0.4	0.02656	0.13277	0.33147
0.6	0.05974	0.19894	0.33008
0.8	0.10611	0.26471	0.32739
1.0	0.16557	0.32979	0.32301
1.2	0.23795	0.39378	0.31659
1.4	0.32298	0.45627	0.30787
1.6	0.42032	0.51676	0.29667
1.8	0.52952	0.57477	0.28293
2.0	0.65003	0.62977	0.26675
2.2	0.78120	0.68132	0.24835
2.4	0.92230	0.72899	0.22809
2.6	1.07252	0.77246	0.20646
2.8	1.23099	0.81152	0.18401
3.0	1.39682	0.84605	0.16136
3.4	1.74696	0.90177	0.11788
3.8	2.11605	0.94112	0.08013
4.2	2.49806	0.96696	0.05052
4.6	2.88826	0.98269	0.02948
5.0	3.28329	0.99155	0.01591
5.4	3.68094	0.99616	0.00793
5.8	4.07990	0.99838	0.00365
6.2	4.47948	0.99937	0.00155
6.6	4.87931	0.99977	0.00061
7.0	5.27926	0.99992	0.00022
7.4	5.67924	0.99998	0.00007
7.8	6.07923	1.00000	0.00002

<sup>1</sup> After Howarth L., Proc. Roy. Soc., London, A 164, 547, 1938 (by permission).

Table B-18. Values of the constants in the heat transfer equation for laminar flow of generalized Newtonian fluid<sup>1</sup>

<i>m</i>	<i>i</i>	$\lambda_i$	$A_i'$	$A_i''$	$A_i'''$	$C_i$	$f(\epsilon)$
2	1	7.3153	1.46622	0.3360	-0.8020	0.5585	$(5-11\epsilon)/24$
	2	44.6090	-0.802476	-0.1254	0.0719	-0.1216	
	3	113.921	0.587094	0.0579	-0.0207	0.05537	
3	1	6.582	1.493	0.349	-0.944	0.16341	$(24-59\epsilon)/112$
	2	39.09	-0.850	-0.147	0.092	-0.03654	
	3	99.50	0.643	0.079	-0.039	0.01786	
4	1	6.263	1.516	0.3575	-0.092	0.17708	$(28-76\epsilon)/128$
	2	36.35	0.866	-0.1631	0.1072	-0.040279	
	3	92.34	0.634	0.0865	-0.0308	0.018418	

<sup>1</sup> After Wroński S., Prace Inst. Inż. Chem. PW, nr 1, 1973.

## C. DIAGRAMS

- Figure C-1 Coefficients of compressibility chart
- Figure C-2 Diagram due to Hougen and Watson for determination of fugacity coefficient of gases
- Figure C-3 Watson diagram for liquid density determination (chart for coefficient of expansion)
- Figure C-4 Diagram due to Hougen and Watson for determination of pressure correction for molar capacity of gases
- Figure C-5 Diagram due to Hougen and Watson for determination of pressure correction for enthalpy of gases (moderate pressure range)
- Figure C-6 Diagram due to Hougen and Watson for determination of pressure correction for enthalpy of gases (high pressure range)
- Figure C-7 Diagram due to Hougen and Watson for determination of pressure correction for entropy of gases
- Figure C-8 Carr diagram for determination of pressure correction for gas viscosity
- Figure C-9 Diagram due to Uyehara and Watson for determination of reduced viscosity
- Figure C-10 Diagram of function  $\Phi_{1,2}$  for determination of viscosity of gaseous mixtures according to the Wilke equation
- Figure C-11 Diagram due to Comings for determination of pressure correction for thermal conductivity of gases
- Figure C-12 Diagram due to Gamson for determination of reduced thermal conductivity
- Figure C-13 Diagram due to Slattery for determination of pressure correction for the coefficients of self-diffusion of gases
- Figure C-14 Diagram due to Wilke for determination of diffusivity in diluted liquid solutions
- Figure C-15 Diagram due to Wilke and Chang for determination of diffusivity in diluted liquid solutions
- Figure C-16 Enthalpy diagram for potassium chloride-water system.
- Figure C-17 Enthalpy diagram for humid air at 0.1 MPa
- Figure C-18 Enthalpy diagram for naphthalene-air system at 0.1 MPa
- Figure C-19 Entropy diagram for naphthalene-air system
- Figure C-20 Diagram for determination of extreme concentration during unsteady-state diffusion in solid bodies
- Figure C-21 Diagram for determination of average concentration during unsteady-state diffusion in solid bodies
- Figure C-22 Diagram due to van Krevelen and Hofstijzer for determination of the mass transfer coefficient with second order chemical reaction

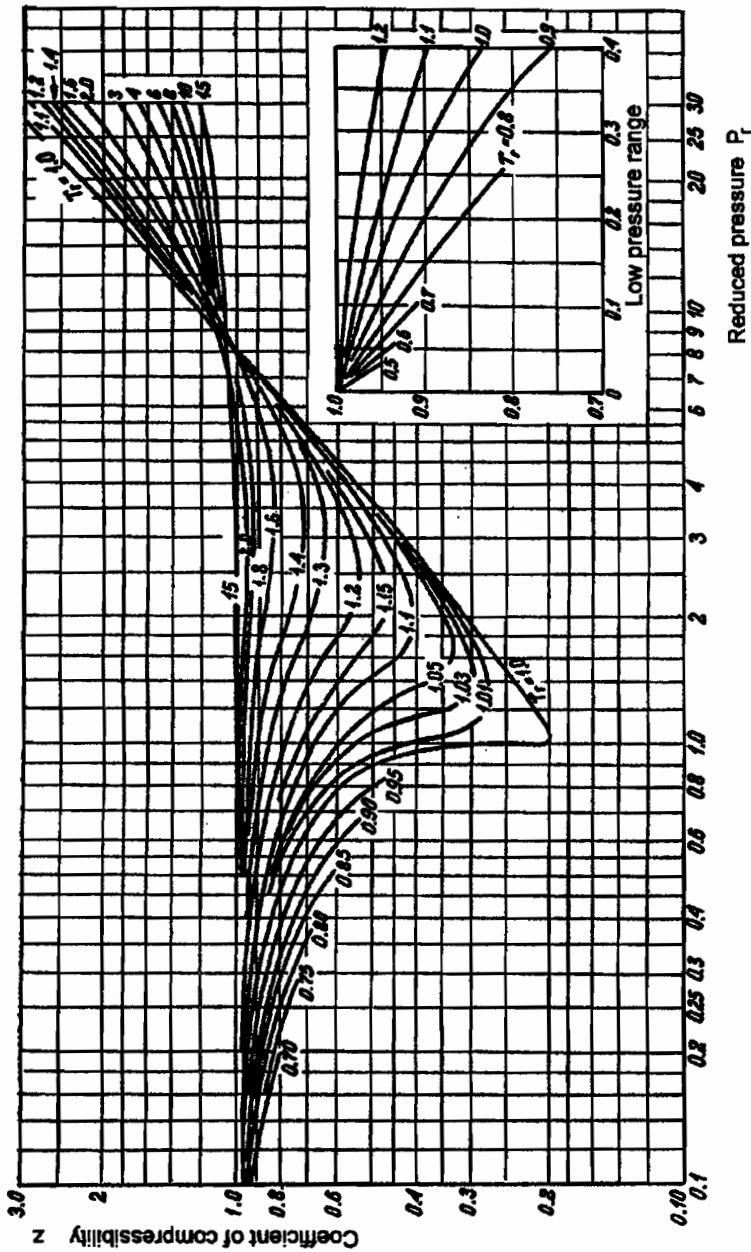


Figure C-1. Coefficients of compressibility chart (after Hougen O. A., Watson K. M., and Ragatz R. A., *Chemical Process Principles*, Part II, *Thermodynamics*, John Wiley, New York, 1959).

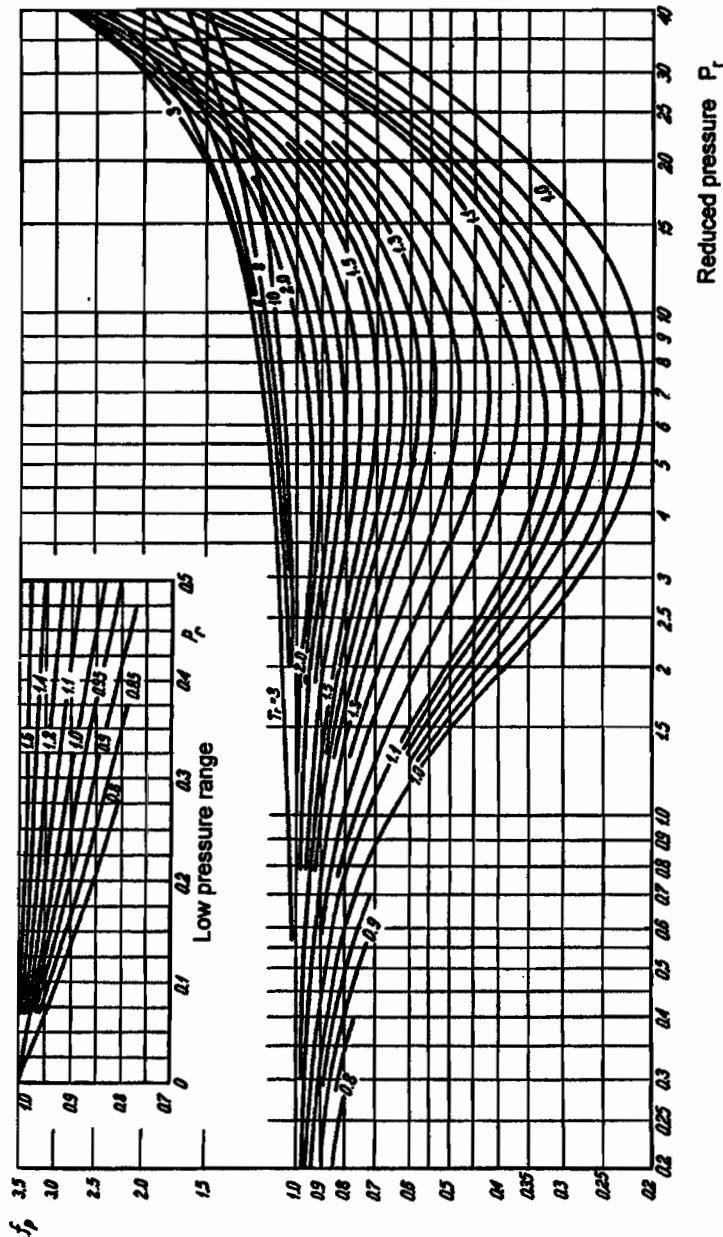


Figure C-2. Diagram due to Hougen and Watson for determination of fugacity coefficient of gases  
 (after Bretsznajder S., *Prediction of Transport and Other Physical Properties of Fluids*,  
 Pergamon Press, Oxford, 1971)

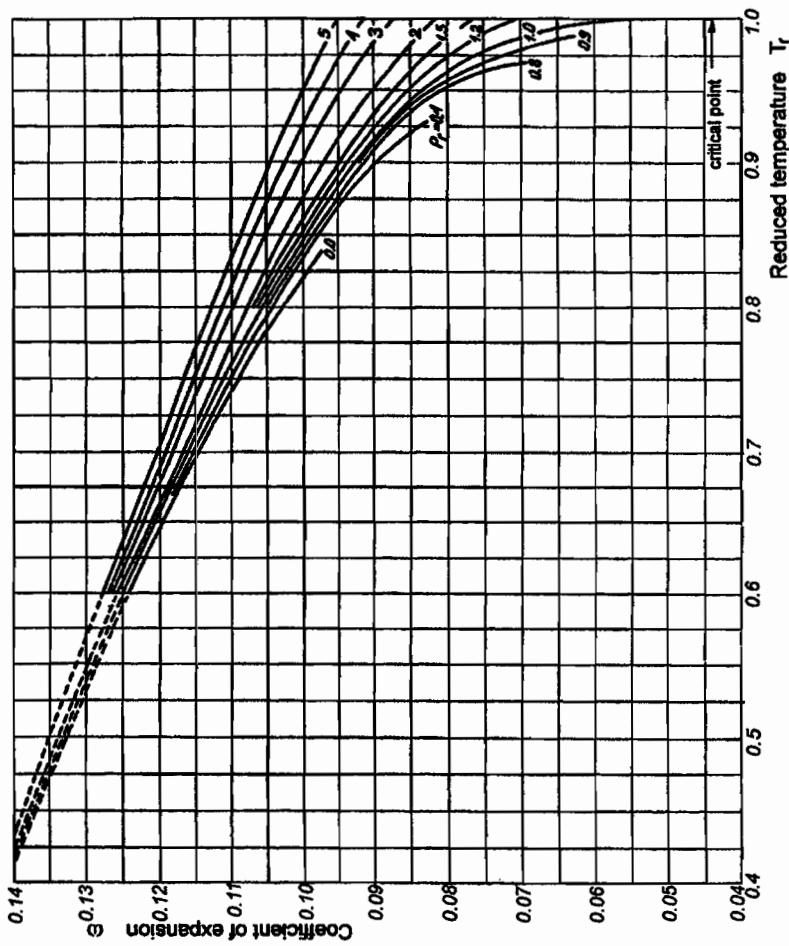


Figure C-3. Watson diagram for liquid density determination (chart for coefficient of expansion),  
(after Breitsnajder S., *Prediction of Transport and Other Physical Properties of Fluids*,  
Pergamon Press, Oxford, 1971).

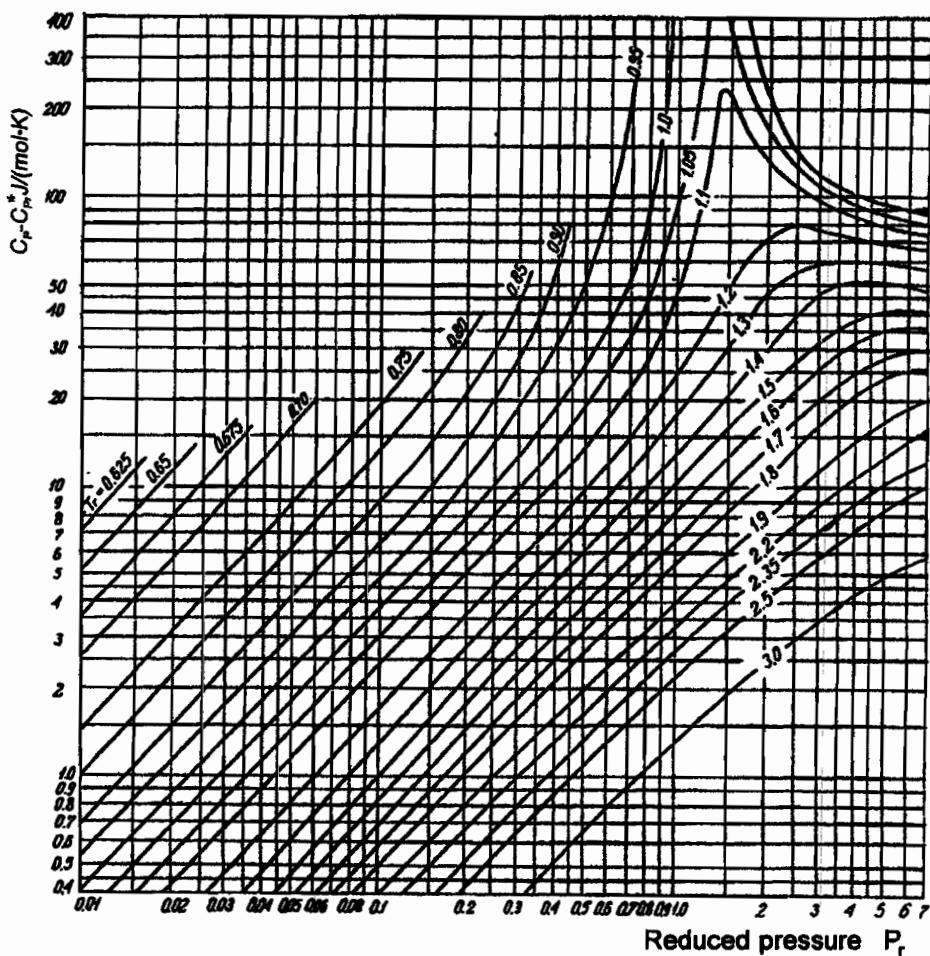


Figure C-4. Diagram due to Hougen and Watson for determination of pressure correction for molar capacity of gases (after Bretsznajder S., *Prediction of Transport and Other Physical Properties of Fluids*, Pergamon Press, Oxford, 1971).

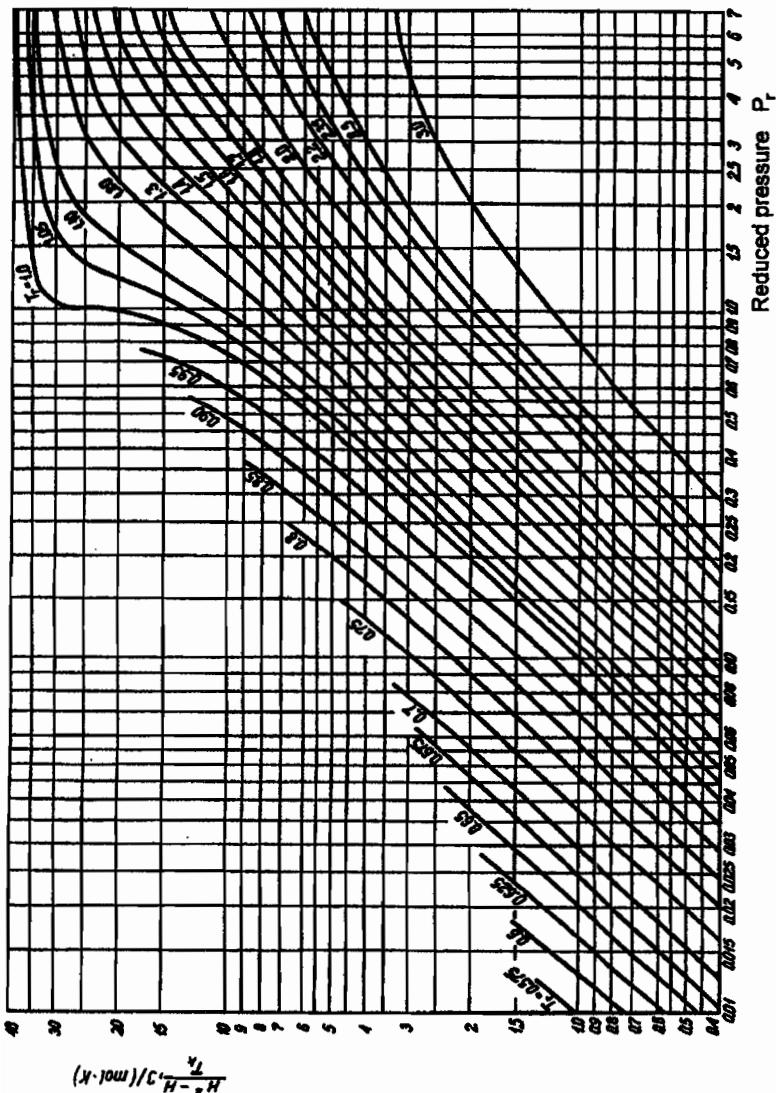


Figure C-5. Diagram due to Hougen and Watson for determination of pressure correction for enthalpy of gases (moderate pressure range), (after Bretsznajder S., *Prediction of Transport and Other Physical Properties of Fluids*, Pergamon Press, Oxford, 1971).

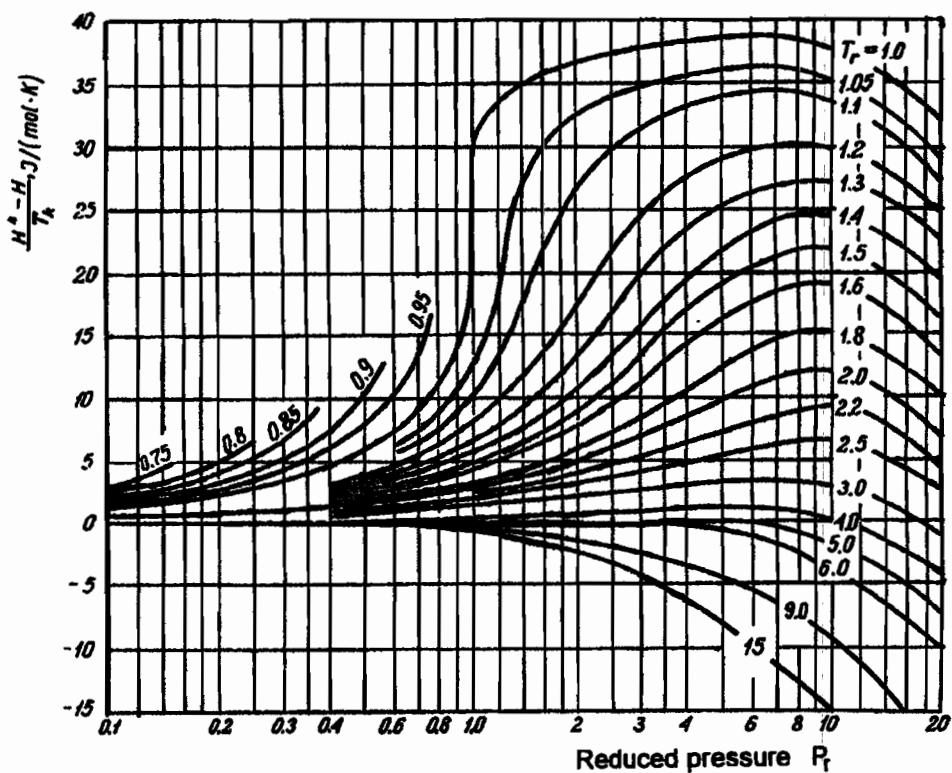


Figure C-6. Diagram due to Hougen and Watson for determination of pressure correction for enthalpy of gases (high pressure range),  
(after Bretsznajder S., *Prediction of Transport and Other Physical Properties of Fluids*), Pergamon Press, Oxford, 1971.

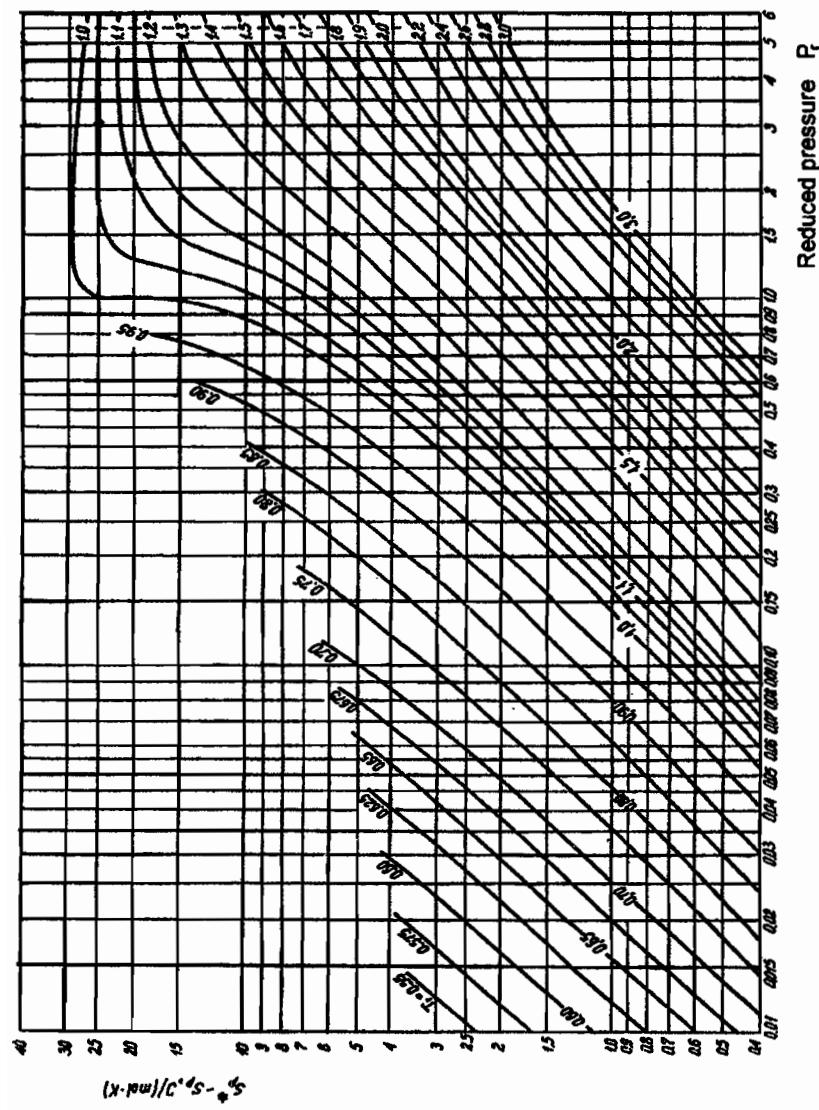


Figure C-7. Diagram due to Hougen and Watson for determination of pressure correction for entropy of gases  
 (after Bretschnajder S., *Prediction of Transport and Other Physical Properties of Fluids*,  
 Pergamon Press, Oxford, 1971).

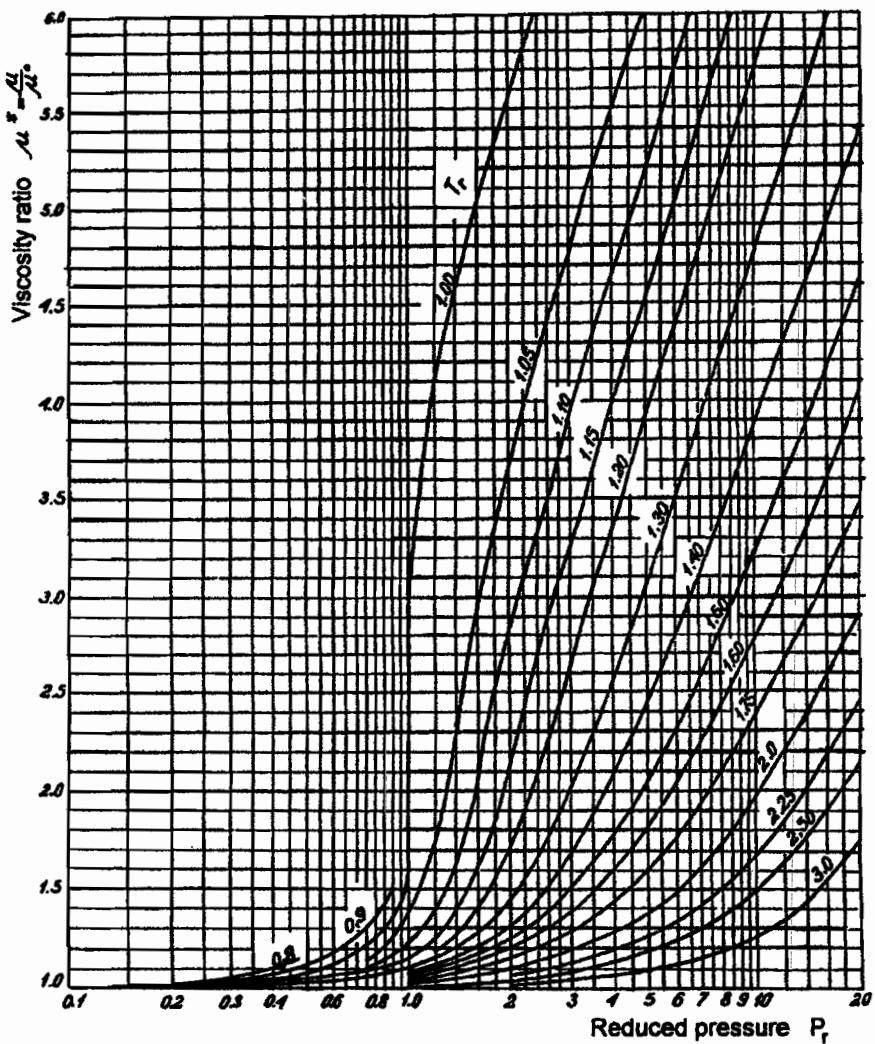


Figure C-8. Carr diagram for determination of pressure correction for gas viscosity (after Carr N. L., Kobayashi R., and Burroughs D. B., *Am. Inst. Min. and Met. Engrs, Petroleum Tech.*, 6, 47, 1954).

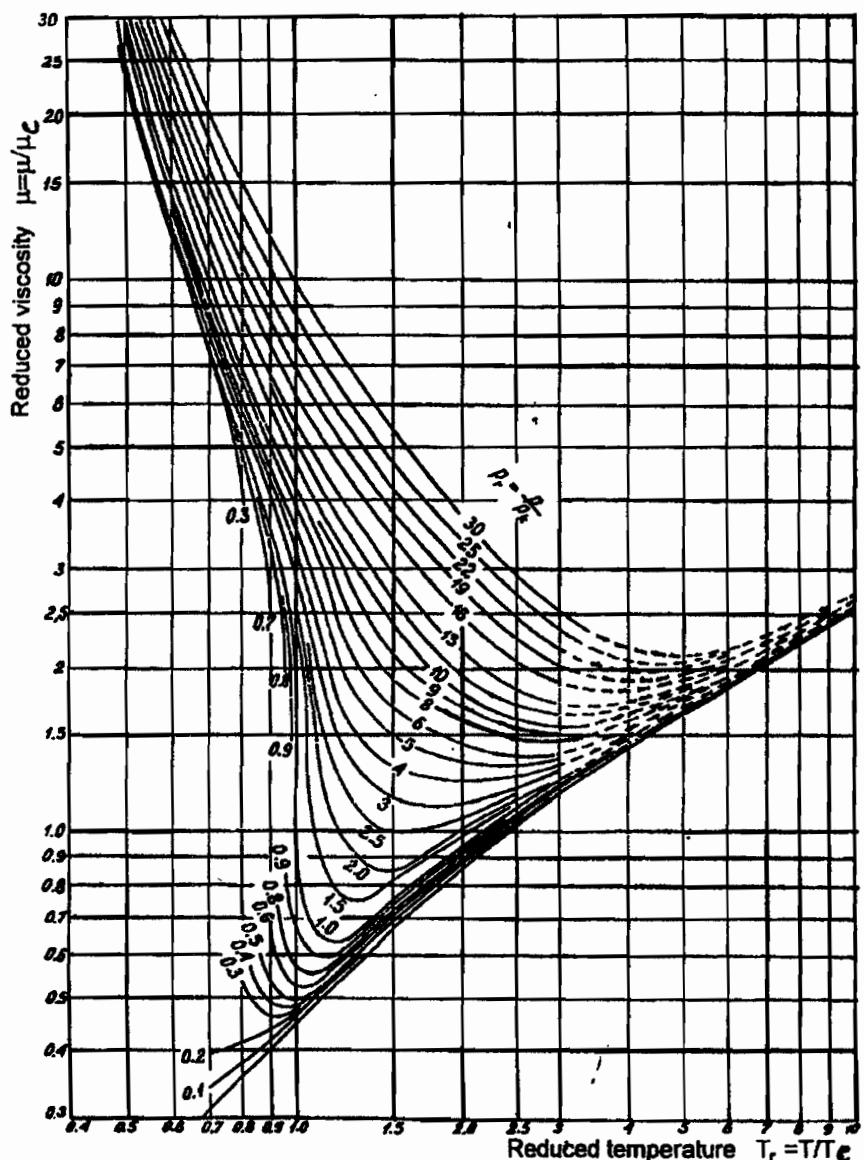


Figure C-9. Diagram due to Uyehara and Watson for determination of reduced viscosity  
(after Bretsznajder S., *Prediction of Transport and Other Physical Properties of Fluids*, Pergamon Press, Oxford, 1971).

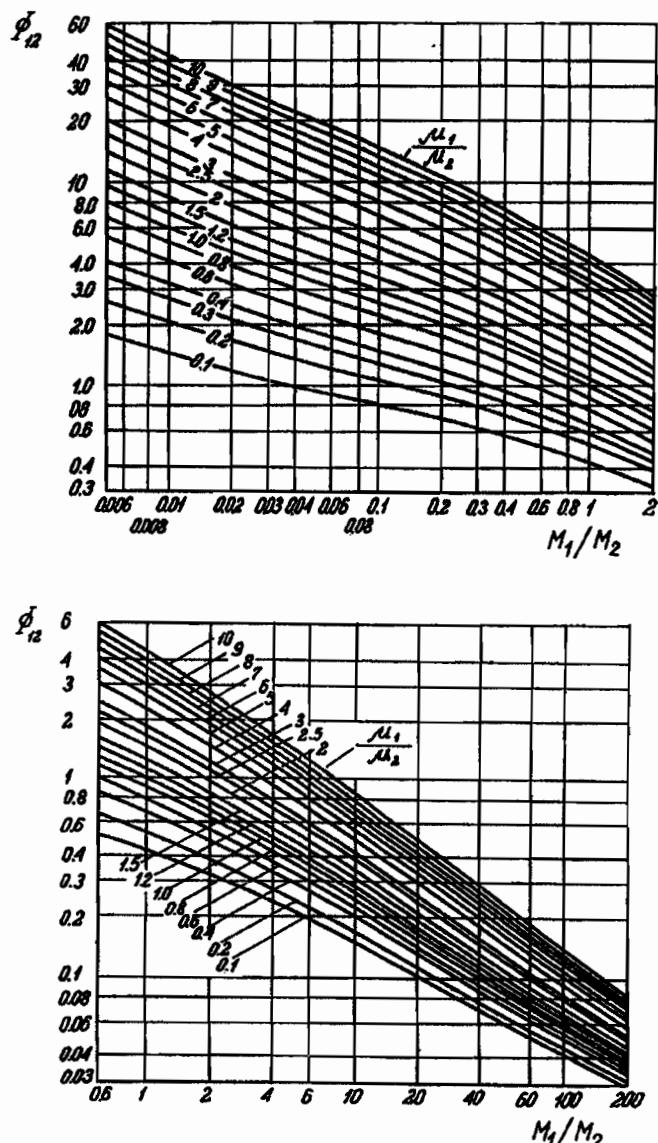


Figure C-10. Diagram of function  $\Phi_{1,2}$  for determination of viscosity of gaseous mixtures according to Wilke equation (after Bromley A. L., and Wilke C. R., *Ind. Eng. Chem.*, 43, 1641, 1959).

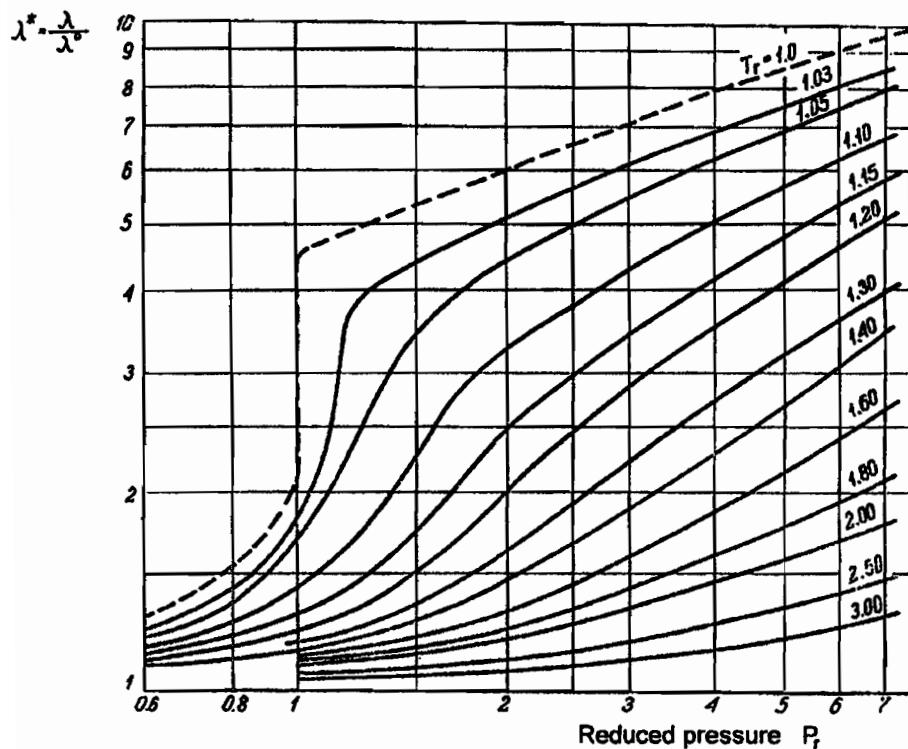


Figure C-11. Diagram due to Comings for determination of pressure correction for thermal conductivity of gases (after Lenoir J. M., Junk W. A., and Comings E. W., *Chem. Eng. Progr.*, 49, 539, 1953).

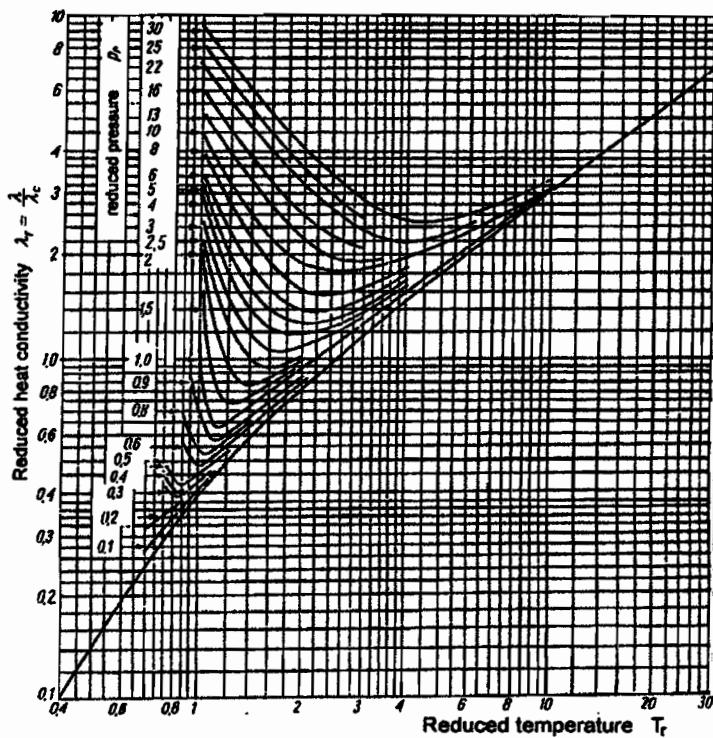


Figure C-12. Diagram due to Gamson for determination of reduced thermal conductivity (after Gamson B. W., *Chem. Eng. Progr.*, 45, 154, 1949).

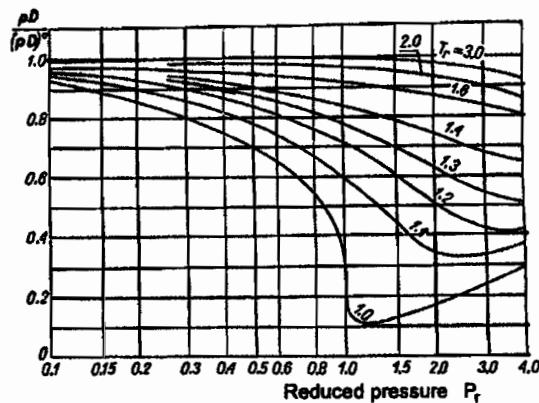


Figure C-13. Diagram due to Slattery for determination of pressure correction for the coefficient of self-diffusion of gases (after Bird R. B., Stewart W. E., and Lightfoot E. N., *Transport Phenomena*, John Wiley, New York, 1960).

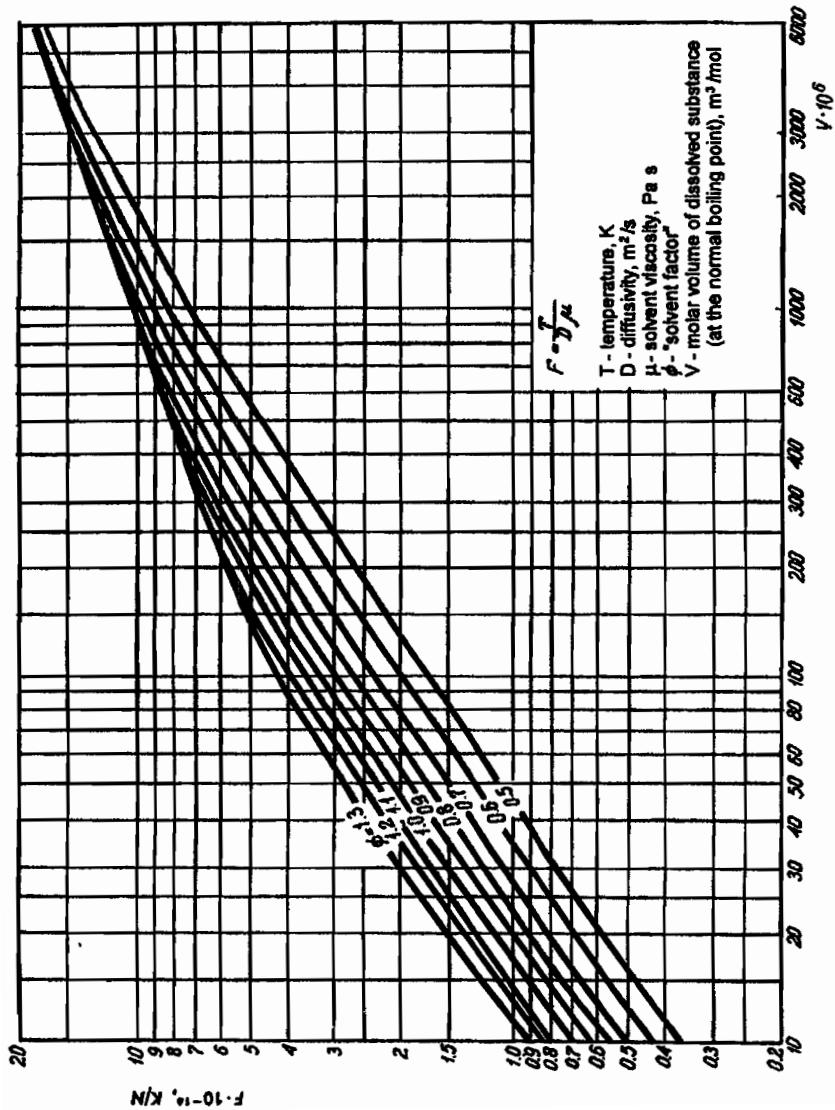


Figure C-14. Diagram due to Wilke for determination of diffusivity in diluted liquid solutions  
(after Wilke C. R., *Chem. Eng. Progr.*, 45, 218, 1949).

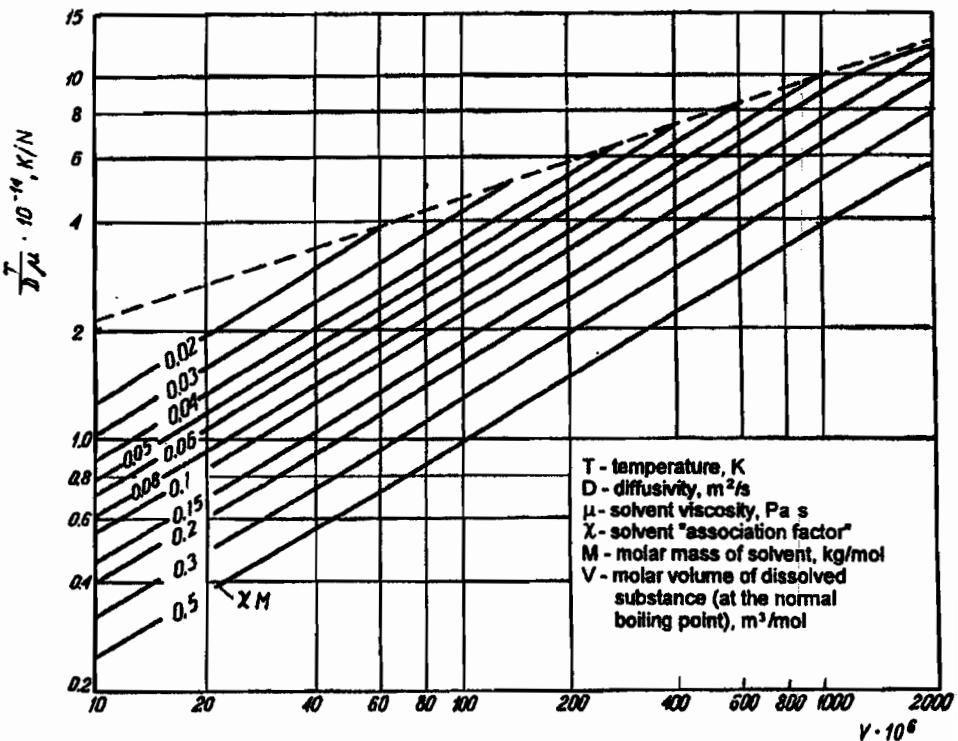


Figure C-15. Diagram due to Wilke and Chang for determination of diffusivity in diluted liquid solutions (after Wilke C. R., and Chang P., *Am. Inst. Chem. Eng. J.*, 1, 264, 1955).

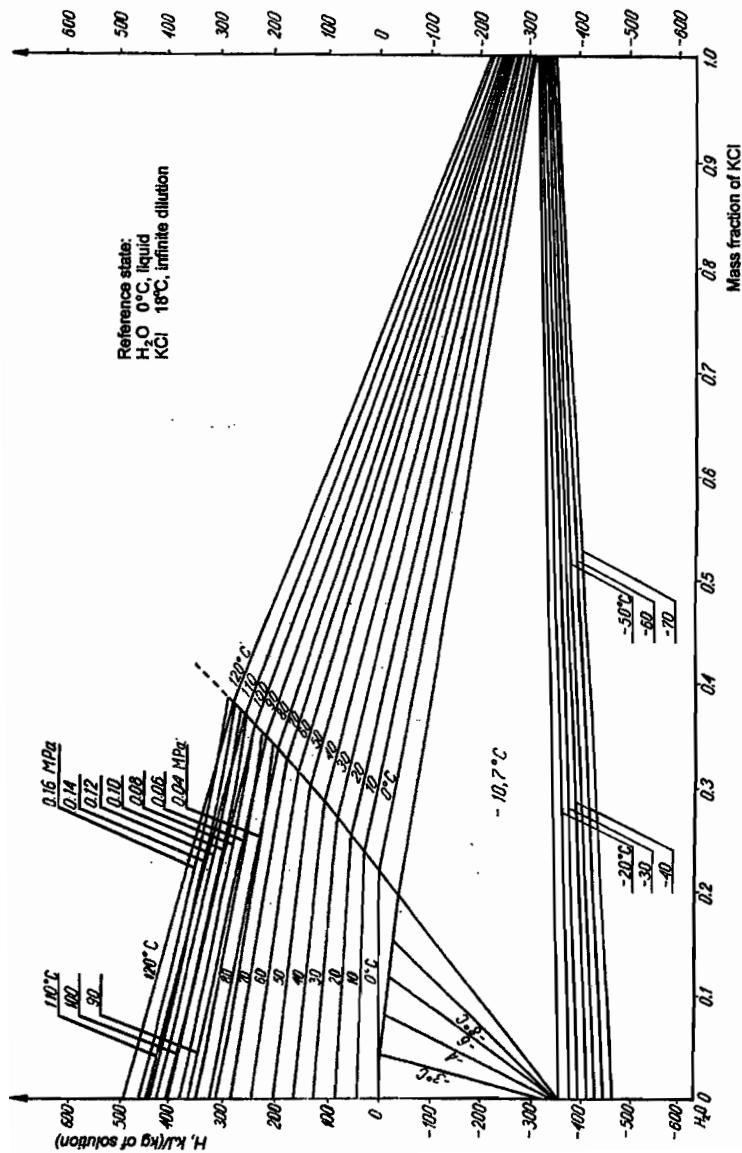


Figure C-16. Enthalpy diagram for potassium chloride-water system.

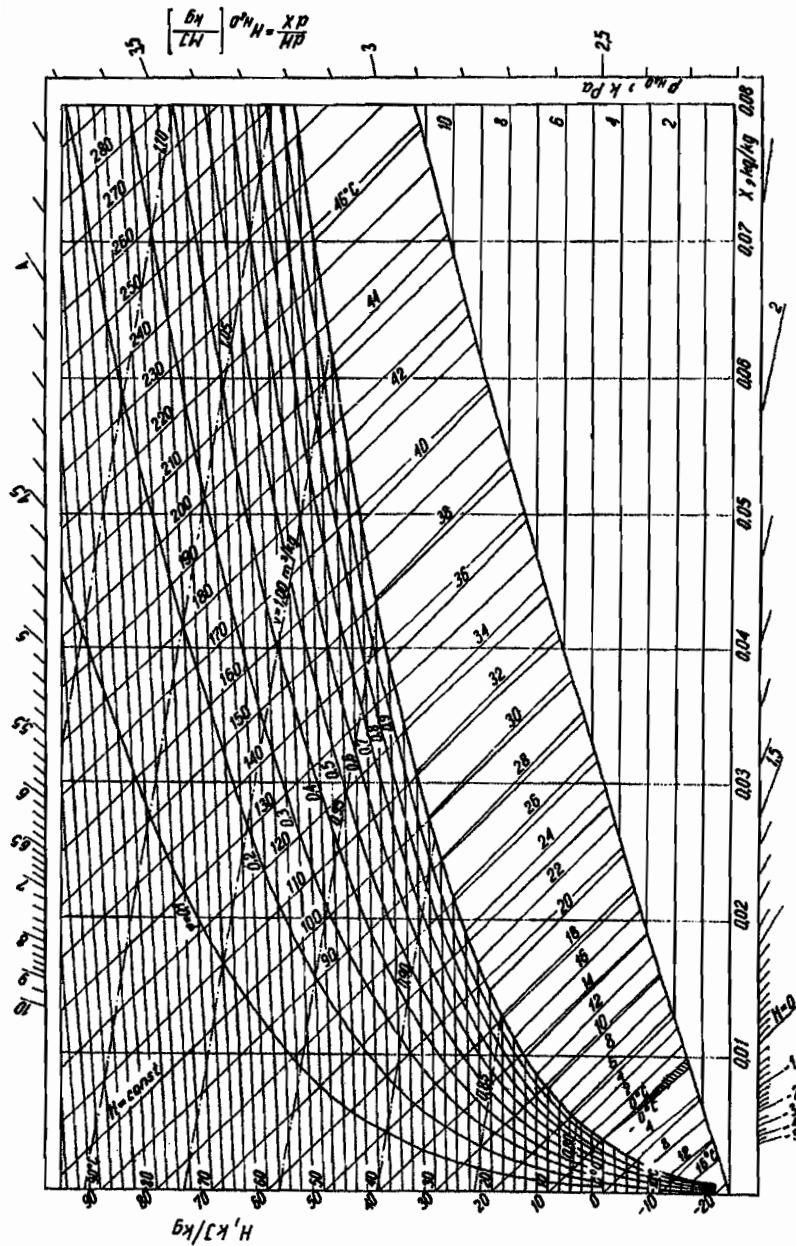


Figure C-17. Enthalpy diagram for humid air at 0.1 MPa (after Ražnjević K., *Thermal Properties and Diagrams*, Technička Knjiga, Zagreb, 1964).

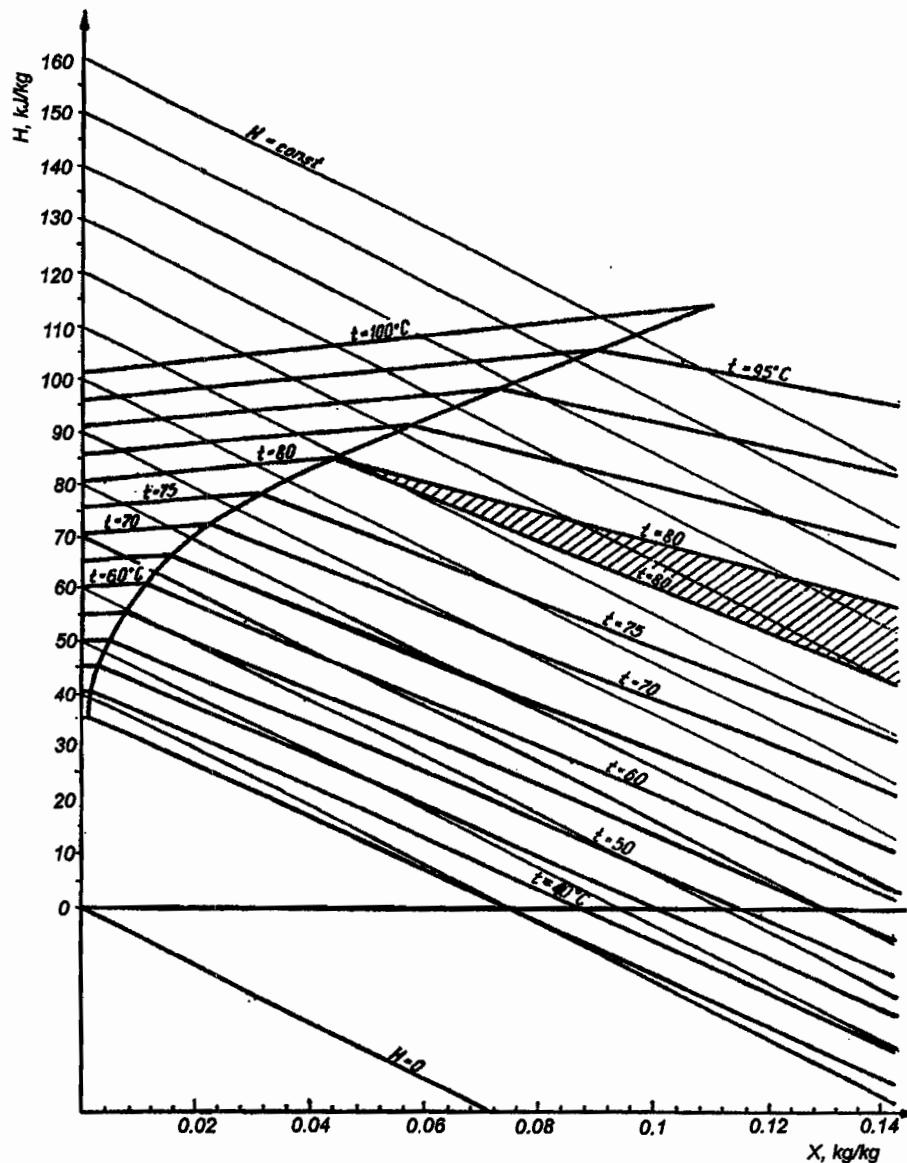


Figure C-18. Enthalpy diagram for naphthalene-air system at 0.1 MPa.

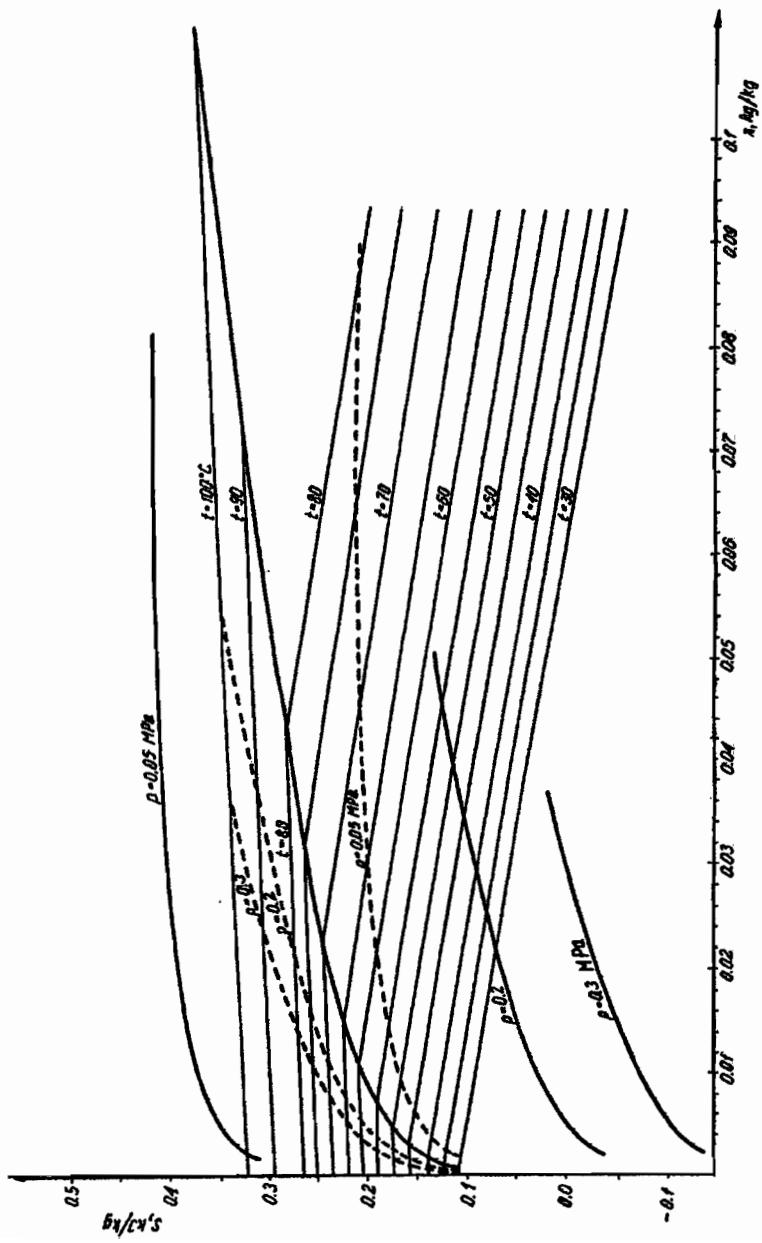


Figure C-19. Entropy diagram for naphthalene-air system.

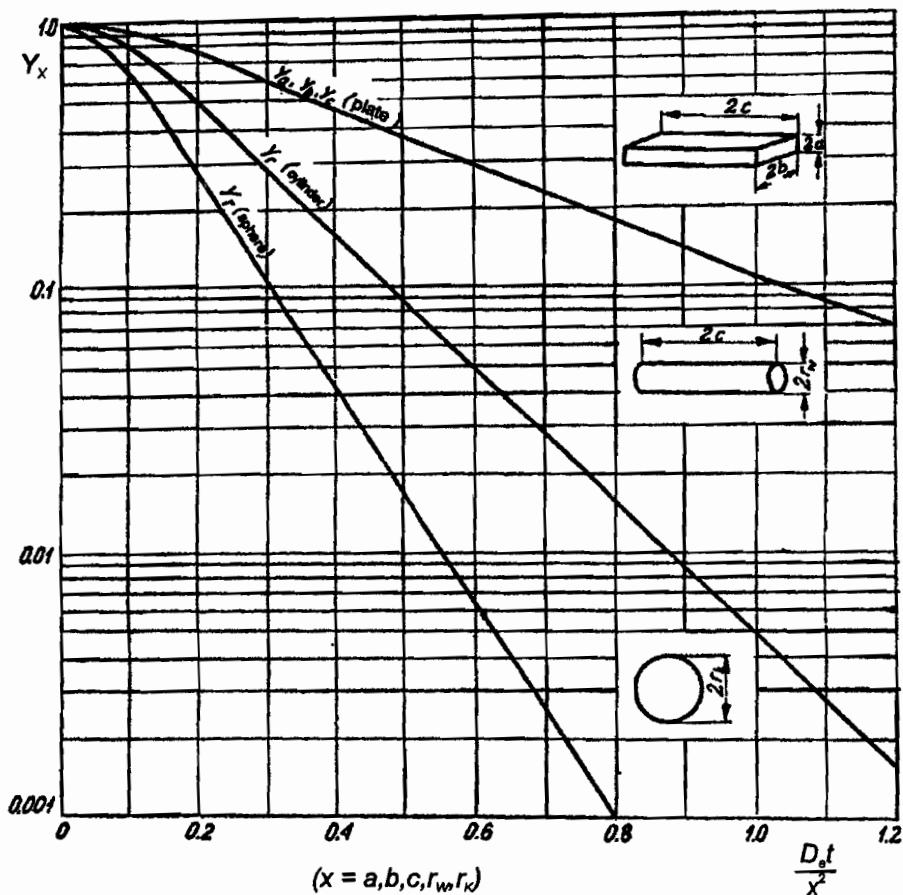


Figure C-20. Diagram for determination of extreme concentration during unsteady-state diffusion in solid bodies (after Treybal R. E., *Mass Transfer Operations*, 2nd ed., McGraw-Hill, New York, 1965).

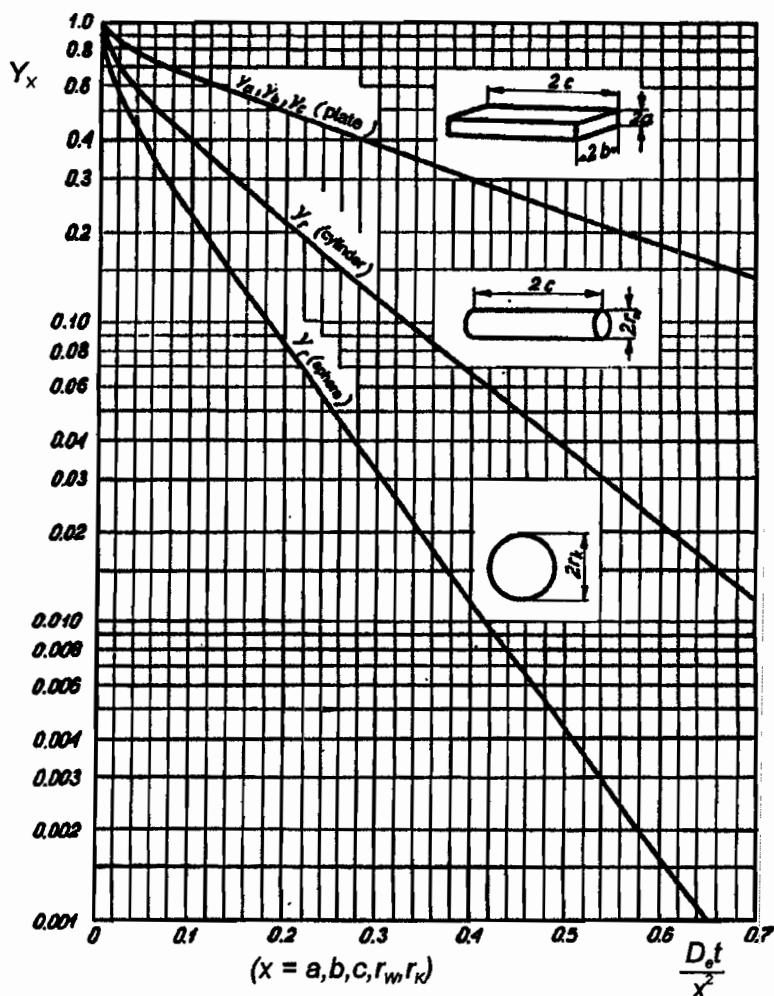


Figure C-21. Diagram for determination of average concentration during unsteady-state diffusion in solid bodies (after Treybal R. E., *Mass Transfer Operations*, 2nd ed., McGraw-Hill, New York, 1965).

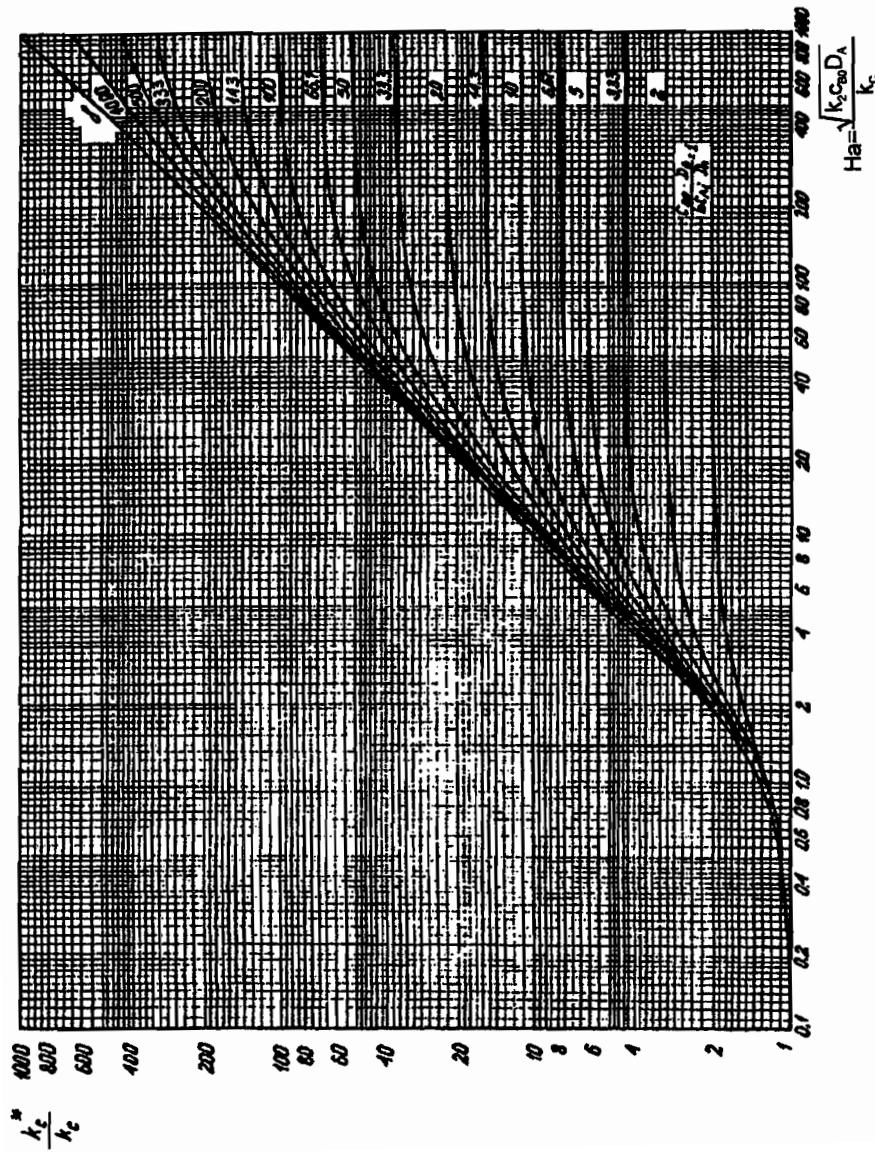


Figure C-22. Diagram due to van Krevelen and Hofijzer for determination of the mass transfer coefficient with second order chemical reaction (after Ramm V. N., *Gas Absorption*, Khimya, Moscow, 1966).

# INDEX

## A

Absorption equilibrium, 90, 91, 334  
Activity, 98  
  coefficient, 82, 90, 98  
Adiabatic expansion, 9, 110  
Adiabatic flame temperature, 5, 7  
Adsorption equilibrium, 102, 103  
Analogy between momentum, heat  
  and mass transfer, 290  
Arrhenius equation, 310

## B

Beattie-Bridgeman equation of state, 33, 330  
Bingham fluid, 129  
Biot number, 163, 366  
Bodenstein number, 188, 366  
Boundary conditions encountered in  
  heat transfer, 163, 166, 174  
  mass transfer, 204, 206, 207, 211, 214  
Boundary layer, 138, 141  
  laminar, 138  
  turbulent, 141, 143  
Brinkman number, 171, 175, 366

## C

Carnot cycle, 17  
Chemical conversion, 111, 113  
Chemical equilibrium, 111, 112  
Chemical reaction  
  consecutive, 298  
  heterogeneous, 311  
  instantaneous, 301  
  irreversible, 308  
  reversible, 304  
  standard enthalpy of, 5, 114  
  standard entropy of, 114  
Chilton-Colburn analogy, 286, 290  
Combustion, 4, 312

Compressibility factor, 29, 391  
Compression, 19  
Condensation, 288  
Conduction, 162  
Conductivity  
  of gas, 64, 67  
Constant-pressure molar heat, 45  
Continuity equation, 202, 349  
Convection heat transfer coefficient,  
  163, 167  
  correlation, 354  
Convection mass transfer coefficient,  
  223  
  correlation, 359  
Coutte flow, 136  
Crystallization equilibrium, 106  
“Cup-mixed” concentration, 229  
Cycle, 17, 21, 23

## D

Darcy-Weisbach equation, 8  
Density  
  of gases, 32, 36  
  of liquids, 38, 42  
Diffusion  
  in anisotropic materials, 219  
  steady-state, 197, 201  
  unsteady-state, 204, 205, 207  
Diffusion coefficient  
  gas diffusion coefficient, 69  
    Wilke equation for gas mixture, 73  
    Loschmidt cell for measuring, 216  
  liquid diffusion coefficient, 74  
    “effective” diffusion coefficient, 204  
Diffusion through a stagnant film, 197  
Diffusivity  
  of gas, 69  
  of liquid, 74

Dispersed systems  
 mass transfer in, 258, 263  
 Dispersion, 278  
 Dissipation function for viscous flow, 174  
 Dissipative effects, 170  
 Drag coefficient, 143, 147  
 local, 140  
 Dühring method, 61

**E**

Eddy diffusivity, 251  
 Energy balance, 1, 327  
 of a non stationary process, 3, 327  
 Energy equation, 162, 177, 348, 349

Enthalpy  
 diagram, 24, 95, 105, 107, 108  
 of gas, 46  
 Entropy  
 balance, 14  
 of gas, 47  
 Entrance length, correlation for heat transfer coefficients, 167  
 Equation of continuity, 202, 349  
 Equation of motion, 119, 344  
 Equations of state, 330  
 Beattie-Bridgeman, 33  
 Lee-Kesler, 34  
 Peng-Robinson, 39  
 perfect gas, 28  
 Redlich-Kwong, 32  
 Van der Waals, 26  
 virial, 330  
 Equimolar counterdiffusion, 216

**F**

Fick's second law of diffusion, 206,  
 Flat plate  
 laminar flow over, 138  
 mass transfer, 223  
 with chemical reaction, 243  
 turbulent flow over, 141  
 Flow curve, 129  
 Forced convection heat transfer  
 for laminar flow in tube, 166, 169  
 for turbulent flow in tube, 183

past single spheres, 185  
 Forced convection mass transfer  
 for laminar flow in tube, 229  
 for turbulent flow in tube, 251  
 Fourier number  
 for heat transfer, 367  
 for mass transfer, 204, 367  
 Friction factor  
 Darcy, 8  
 Fanning, 290  
 Fröessling equation, 185, 267  
 Fugacity, 76  
 coefficient chart, 392  
 in mixture, 92, 115

**G**

Gas bubbles, 159  
 Gas density, 32  
 Gas fugacity, 76  
 Gas viscosity, 52  
 Generalized charts  
 compressibility, 391  
 enthalpy, 395, 396  
 entropy, 397  
 fugacity, 392  
 Graetz number, 169, 368  
 Graetz problem, 166  
 Grashof number  
 for heat transfer, 163, 368  
 for mass transfer, 368

**H**

Hatta number, 307, 308, 368  
 Heat  
 capacity, 45  
 convection, 163, 167  
 diffusivity, 164  
 of formation, 4  
 Hedström number, 130, 368  
 Helmholtz function, 49  
 Henry's law, 90, 305  
 Higbie's model, 300  
 Humidity, 107  
 Hydraulic diameter, 156

- I**
- Ideal gas
    - density, 10
    - specific heat capacity, 9
  - Isoentropic
    - process, 12
    - efficiency, 13
  - Irreversible process, 15, 17
- J**
- J-factor for heat transfer, 286,
  - J-factor for mass transfer, 286, 351
  - Joule-Thomson coefficient, 27
- K**
- Karman momentum balance equation, 141
  - Kay's rule, 35
  - Kinematic viscosity, 164
  - Kinetic energy of fluid, 132
  - Kinetics of chemical reactions, 297, 298, 311, 315
- L**
- Laminar flow,
    - in channel, 125
    - in pipes, 119, 130, 134
    - over plate, 139
  - Laplace transformation, 206
  - Lee-Kesler equation of state, 34, 332
  - Lennard-Jones force constants, 52, 382
  - Lewis-Randall rule, 92
  - Liquid density, 38, 42
  - Liquid-liquid equilibrium, 96, 98
  - Liquid viscosity, 62
  - Log-mean concentration difference, 227, 232, 254
  - Lost work, 8
- M**
- Mass transfer
    - in dispersed system, 258, 263, 266
    - in tube, 229, 251
    - with chemical reaction, 239, 243, 300, 302
- N**
- Non-Newtonian fluid, 129
  - Nusselt number, 164, 369
- O**
- Overall mass transfer coefficient, 274, 275
- P**
- Packed bed, 154, 156
    - mass transfer in, 270, 272, 273
  - Partial molar volume, 90, 386
    - apparent, 92, 387
  - Partial pressure, 80
  - Péclet number, 237
  - Peng-Robinson equation of state, 39, 332
  - Poiseuille equation, 120, 131
  - Power-law fluid, 134, 136
  - Prandtl number, 163, 369
  - Pressure
    - critical, 32
    - reduced, 32, 36
  - Pseudocritical parameters, 35, 92
  - Pseudoplastic fluid, 134
  - Psychrometric measurements, 285
- R**
- Rabinovitsch equation, 130
  - Radiation
    - heat transfer coefficient, 165
  - Rankin cycle, 23
  - Raoult's law, 80
  - Redlich-Kwong equation of state, 32, 331
  - Reduced
    - parameters, 32
    - properties, 42, 52, 66
  - Refrigeration cycle, 23
  - Reversible process, 17

Reversible work, 12  
 Reynolds number, 120, 352, 369  
 for non-Newtonian fluids, 136

**S**

Saturated vapor, 22, 80  
 Settling  
   free, 147, 184  
   hindered, 150  
 Schmidt number, 224, 369  
 Simultaneous energy and mass transfer,  
   282  
 Shear stress, 123  
 Sherwood number, 223, 370  
 Solid catalyst, 314  
   effectiveness factor, 319  
 Solidification, 191, 194  
 Specific surface, 104  
 Standard state, 5  
 Steam power cycle, 21  
 Stream function, 138  
 Sutherland constant, 54, 67, 385

**T**

Temperature  
   critical, 32  
   reduced 32, 36  
 Temperature distribution  
   in flow with internal heat source, 181  
   in heated rod, 163  
   in gap, 171  
 Thermal conductivity  
   of gases, 64, 67  
 Thermal diffusivity, 194  
 Thermal expansion coefficient, 164  
 Thermodiffusion, 221  
 Thermodynamic functions, 25, 46  
 Tie-line, 96, 101  
 Tortuosity, 153, 156  
 Turbulent flow  
   in boundary layer, 141, 143

**V**

Van der Waals equation of state, 26, 330  
 Van't Hoff isotherm, 113  
 Vapor-liquid equilibrium  
   in perfect system, 80  
   in real system, 82  
 Velocity profile in laminar flow  
   in channels, 124, 126  
   in pipes, 120, 133, 135  
   over plate, 139  
 Virial equation of state, 330  
 Volatility, 80

**W**

Weber number, 146, 370  
 Wetted-wall column  
   mass transfer in , 225, 256  
 Work  
   loss, 2  
   reversible, 12  
   technical, 2