IChemE

Student pocketbook

Concepts, principles and formulae for chemical engineering students

Foreword

This is the essential reference guide to the basic formulae, data and definitions you'll need throughout your chemical, biochemical or process engineering career.

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Contents

Inorganic chemistry

Common definitions

Atomic number – the number of protons in the nucleus of an atom.

Avogadro's number – the number of molecules (6.023×10^{23}) in one gram-mole of a substance.

Equilibrium constants for the reaction $aA + bB = cC + dD$

where reaction is in solution

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b} \qquad \text{([ ] refers to molarity)}$$

where reaction is in the gas phase

$$K_p = \frac{p_C^c p_D^d}{p_A^a p_B^b} \qquad (p = \text{partial pressure})$$

Gram equivalent weight –

- (nonredox reaction) the mass in grams of a substance equivalent to 1 gram-atom of hydrogen, 0.5 gram-atom of oxygen, or 1 gram-ion of the hydroxyl ion. It can be determined by dividing the molecular weight by the number of hydrogen atoms or hydroxyl ions (or their equivalent) supplied or required by the molecule in a given reaction.
- (redox reaction) the molecular weight in grams divided by the change in oxidation state.

Ion product of water (K_w) – the product of the hydrogen ion and hydroxyl ion concentrations in gram-ions per litre

$$K_w = [\mathrm{H}^+][\mathrm{OH}^-]$$

Mass number – the number of protons plus the number of neutrons in the nucleus of an atom.

Molality (m) – (gram moles of solute)/(kilograms of solvent).

Molarity (M) – (gram moles of solute)/(litres of solution).

Normality (N) – (gram equivalents of solute)/(litres of solution).

Oxidation – the loss of electrons by an atom or group of atoms.

pH – the negative logarithm (base 10) of the hydrogen ion concentration in gram ions per litre:

$$p\mathrm{H} = -\log_{10}[\mathrm{H}^+]$$

Reduction – the gain of electrons by an atom or group of atoms.

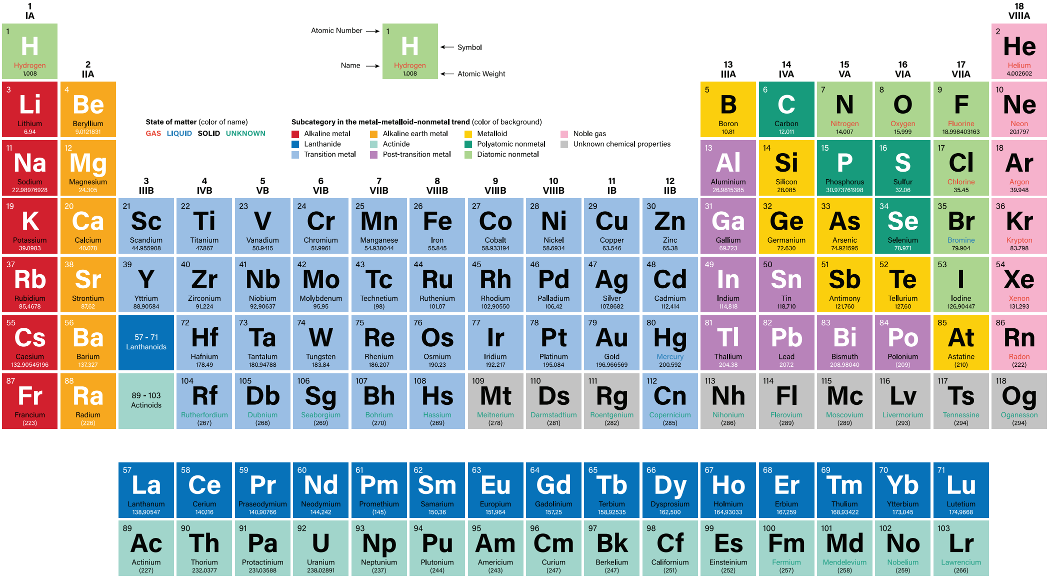
Solubility product (S.P. or K_{sp}) – for the slightly soluble solid, A_aB_b, dissolving

$$A_aB_b\ (\text{solid}) = aA^+(\mathrm{aq}) + bB^-(\mathrm{aq})$$

where A^+ is any cation and B^- is any anion

S.P. or $K_{sp} = [A^+]^a\ [B^-]^b =$ a constant at a given temperature.

Properties of chemical elements



Atomic Number → 1
H ← Symbol
Name → Hydrogen
1.008 ← Atomic Weight

State of matter (color of name)
GAS LIQUID **SOLID** UNKNOWN

Subcategory in the metal–metalloid–nonmetal trend (color of background)
- ■ Alkaline metal
- ■ Lanthanide
- ■ Transition metal
- ■ Alkaline earth metal
- ■ Actinide
- ■ Post-transition metal
- ■ Metalloid
- ■ Polyatomic nonmetal
- ■ Diatomic nonmetal
- ■ Noble gas
- ■ Unknown chemical properties

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.008																	2 He Helium 4.002602
3 Li Lithium 6.94	4 Be Beryllium 9.0121831											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998403163	10 Ne Neon 20.1797
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305											13 Al Aluminium 26.9815385	14 Si Silicon 28.085	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955908	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933194	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921595	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90637	42 Mo Molybdenum 95.95	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
55 Cs Caesium 132.90545196	56 Ba Barium 137.327	57 - 71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.592	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 - 103 Actinoids	104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (269)	107 Bh Bohrium (270)	108 Hs Hassium (269)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (286)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)
		57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668	
		89 Ac Actinium (227)	90 Th Thorium 232.0377	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (266)	

Common anions

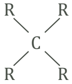
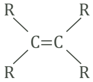
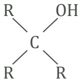
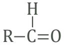
Name	Symbol	Name	Symbol
Acetate	$C_2H_3O_2^-$	Hydroxide	OH^-
Arsenate	$AsO_3^{\equiv}$	Hypochlorite	OCl^-
Arsenite	$AsO_4^{\equiv}$	Iodate	IO_3^-
Bicarbonate	HCO_3^-	Iodide	I^-
Bisulphate	HSO_4^-	Molybdate	$MoO_4^{=}$
Bromate	BrO_3^-	Nitrate	NO_3^-
Bromide	Br^-	Nitrite	NO_2^-
Carbonate	$CO_3^{=}$	Oxalate	$C_2O_4^{=}$
Chlorate	ClO_3^-	Perchlorate	$ClO_4^{=}$
Chloride	Cl^-	Permanganate	MnO_4^-
Chromate	$CrO_4^{=}$	Peroxide	$O_2^{=}$
Cyanamide	$CN_2^{=}$	Phosphate	$PO_4^{\equiv}$
Cyanide	CN^-	Sulphate	$SO_4^{=}$
Dichromate	$Cr_2O_7^{=}$	Sulphide	$S^{=}$
Dithionate	S_2O_6	Sulphite	$SO_3^{=}$
Ferricyanide	$Fe(CN)_6^{\equiv}$	Thiocyanate	CNS^-
Ferrocyanide	$Fe(CN)_6^{==}$	Thiosulfate	$S_2O_3^{=}$
Formate	CHO_2^-		

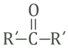
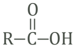
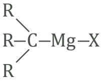
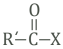
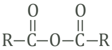
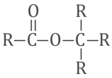
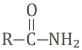
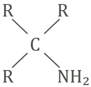
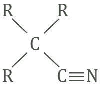
Organic chemistry

Note: for conciseness the following symbols are used:
R = H atom or saturated hydrocarbon group
R' = hydrocarbon group only
X = halogen
n = an integer

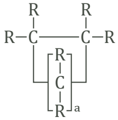
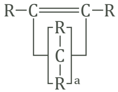
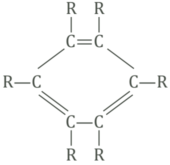
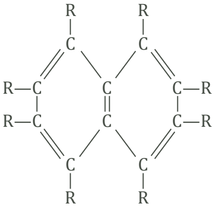
General classes of compounds

The straight and branched chain types of compounds

Type or name	General formula
1. Alkane or paraffin (also saturated hydrocarbons)	
2. Alkene or olefin (unsaturated hydrocarbons)	
3. Alkyne	$R-C\equiv C-R$
4. Alcohol	
5. Ether	$R'-O-R'$
6. Aldehyde	 $R-\overset{H}{\overset{\vert}{C}}=O$

Type or name	General formula
7. Ketone	 $R'-\overset{O}{\overset{\|}{C}}-R'$
8. Carboxylic Acid	 $R-\overset{O}{\overset{\|}{C}}-OH$
9. Grignard reagent	
10. Acyl halide	 $R'-\overset{O}{\overset{\|}{C}}-X$
11. Anhydride	 $R-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-R$
12. Ester	 $R-\overset{O}{\overset{\|}{C}}-O-\underset{\underset{R}{\|}}{\overset{\overset{R}{\|}}{C}}-R$
13. Amide	 $R-\overset{O}{\overset{\|}{C}}-NH_2$
14. Amine (base)	
15. Nitrile	

Cyclic compounds

Type or name	General formula
1. Cycloparaffin	
2. Cycloalkene	
3. Aromatic	
4. Naphthalenic	

Pertinent notes

Markovnikov's (Markownikoff's) Rule for the addition of acids to olefins: the negative group of the acid adds to the carbon atom having the fewest hydrogen atoms.

Mechanisms

1. Free radical (unshared electron)
   (no charge)

$$\begin{array}{cc} & R \\ R: & C^{\circ} \\ & R \end{array}$$

2. Carbonium ion (deficient in electrons)
   (positive charge)
   (carbon with six electrons)

$$\begin{array}{cc} & R \\ R: & C^{+} \\ & R \end{array}$$

3. Carbanion
   (excess of electrons)
   (negative charge)
   (carbon with eight electrons)

$$\begin{array}{cc} & R \\ R: & C:^{-} \\ & R \end{array}$$

Physical chemistry

Amagat's Law of Partial Volumes – the volume of a mixture of gases is equal to the sum of the partial volumes of each component gas. The partial volume of a component gas is the volume which that component would occupy at the same temperature and pressure.

Boiling Point Elevation (ΔT_b) – the following equations hold for a dilute solution of a nonionic nonvolatile solute:

$$\Delta \mathrm{T}_b = K_b m$$

$$K_b = \frac{R\left(T_{bp}\right)^2 M_a}{\Delta H_v(1000)}$$

where

ΔH_v = molal heat of vaporisation of solvent
K_b = molal boiling point elevation constant
m = molality
M_a = solvent molecular weight
R = ideal-gas constant
T_{bp} = solvent boiling point, absolute temperature

Clausius Equation

$$\frac{dp}{dT} = \frac{\Delta H_m}{(V - v)T}$$

where

p = pressure
T = absolute temperature
ΔH_m = molar heat of vaporisation
V = molar vapour volume
v = molar liquid volume

Clausius-Clapeyron Equation – where the volume of liquid can be ignored (or $v = 0$) and where the ideal-gas law holds (or $V = {RT}/{p}$) the Clausius Equation becomes

$$\frac{d\ (\ln p)}{dT} = \frac{1}{p}\frac{dp}{dT} = \frac{\Delta H_m}{RT^2}$$

and with $\Delta H_m =$ constant, integration yields

$$ln\frac{p_2}{p_1} = \frac{\Delta H_m}{R}\left[\frac{T_2 - T_1}{T_1 T_2}\right]$$

The symbols are the same as in sections two and three above.

Dalton's Law of Partial Pressures – the pressure of a mixture of gases is equal to the sum of the partial pressures of each component gas. The partial pressure of a component gas is the pressure which that component would exert if it alone occupied the volume at the same temperature.

Faraday's Laws

First Law: the mass of a substance reacting at the electrodes is directly proportional to the quantity of electricity passed through the solution.

Second Law: the masses of different substances produced during electrolysis are directly proportional to their equivalent weights; 96,496 coulombs of electricity = 1 faraday = electricity to yield 1 gram equivalent of any substance.

Freezing Point Depression (ΔT_f) – The following equations hold for a dilute solution of a nonionic solute in which the solid phase is pure solvent.

$$\Delta T_f = K_f m$$

$$K_f = \frac{R\left(T_{fp}\right)^2 M_a}{\Delta H_f(1000)}$$

where

ΔH_f = molal heat of fusion of solvent
K_f = molal freezing point lowering constant
m = molality
M_a = solvent molecular weight
R = ideal-gas constant
T_{fp} = solvent freezing point, absolute temperature

Gibbs Phase Rule – at equilibrium the number of independent variables (F) required to specify the system is equal to the number of components (C) minus the number of phases (P) plus two, or symbolically $F = C - P + 2$. This form of the phase rule applies to non-reactive systems.

Graham's Law of Diffusion – the rate of diffusion of a gas is inversely proportional to the square root of its density.

Henry's Law – at a constant temperature, the concentration of a gas dissolved in a liquid is directly proportional to the partial pressure of the gas above the liquid.

Raoult's Law

$$p_a = x_a P_a$$

where

p_a = partial pressure of component A in vapour
x_a = mole fraction of A in liquid solution
P_a = vapour pressure of pure liquid A

van't Hoff Reaction Isochore

$$\frac{d\ (\ln K)}{dT} = \frac{\Delta H}{RT^2}$$

at constant pressure

where

$\Delta H =$ heat of reaction

$K =$ reaction equilibrium constant

$R =$ ideal-gas constant

$T =$ absolute temperature

If ΔH is constant,

$$\ln\left(\frac{K_2}{K_1}\right) = \frac{\Delta H}{R}\left[\frac{T_2 - T1}{T_1 T_2}\right]$$

Molar Humidity – moles vapour/mole vapour-free gas

$$Y = \frac{y_a}{1 - y_a} = \frac{p_a}{P - p_a}$$

Humidity – kg vapour/kg vapour-free gas

$$Y' = Y\ \frac{M_a}{M_b}$$

Relative saturation – ratio of partial pressure of vapour to partial pressure of vapour at saturation (vapour pressure)

$$H_r = 100\ \frac{p_a}{P_a}$$

Percentage of saturation – ratio of vapour concentration to vapour concentration at saturation (ratio of molar humidity to saturated molar humidity)

$$H_p = 100\ \frac{Y}{Y_{\text{sat}}} = 100\ \frac{p_a\ (P -\ P_a)}{P_a\ (P -\ p_a)}$$

where

p_a = partial pressure of component A in gas
p_a = vapour pressure of pure liquid A
P = total pressure
M_a = molecular weight of A
M_b = molecular weight of B
y_a = mole fraction of a gas

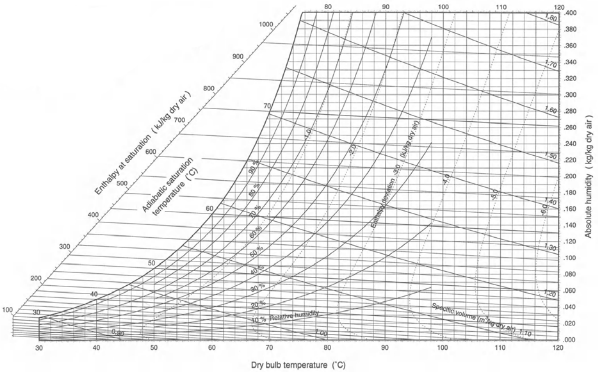


Figure 1. Psychrometric chart of H_2O – Air system at 1 atm, graph from *Handbook of psychrometric charts* by D.C Shallcross 1st edition pg 45.

Fluid flow

Definitions and general equations

Mass velocity

$$G = \bar{V}_{\rho}$$

Simple manometer equation

$$P_1 - P_2 = gh_m(\rho_m - \rho_f)$$

Hagen-Poiseuille equation (laminar flow in long horizontal tube)

$$P_1 - P_2 = \frac{32L\bar{V}\mu}{D^2}$$

Average velocity, $\bar{V}$

$$\bar{V} = \frac{q\text{, volumteric flow rate}}{A\text{, cross-sectional area}}$$

Reynolds number, N_{Re}

$$N_{Re} = \frac{D\bar{V}\rho}{\mu}$$

Bernoulli's equation or mechanical energy balance

$$\frac{P_1}{\rho_1 g} + \frac{\bar{V}_1^2}{2g\alpha_1} + Z_1 = \frac{P_2}{\rho_2 g} + \frac{\bar{V}_2^2}{2g\alpha_2} + Z_2 + H_f + \frac{W_s}{g}$$

where

$\alpha \simeq 1$ for turbulent flow (N_{Re} greater than 10,000 – fully turbulant)

$\alpha = 0.5$ for laminar flow (N_{Re} up to 2100)

Hydraulic radius

$$r_H = \frac{A\text{, cross-sectional area}}{L_p\text{, the wetted perimeter}}$$

Equivalent diameter, D_e

$$D_e = 4\ (\text{hydralic radius, } r_H)$$

Friction

Skin friction

$$H_{fs} = \frac{2fL\bar{V}^2}{gD}$$

Fanning friction factor, f (flow in smooth pipes)

$$\text{Laminar } f = \frac{16\mu}{DV\rho} = \frac{16}{N_{Re}}$$

$$\text{Turbulent } \frac{1}{f^{0.5}} = 4.0\log(N_{Re}f^{0.5}) - 0.4$$

Friction of valves and fittings (add to length of pipe to get total equivalent length)

Fittings and valves	Equivalent resistance, pipe diameters
45-degree elbows	15
90-degree elbows (standard radius)	32
90-degree square elbows	60
180-degree close return bends	75
T's (used as elbow, entering run)	60
T's (used as elbow, entering branch)	90
Couplings	Negligible
Unions	Negligible
Gate valves (open)	7
Globe valves (open)	300
Angle valves (open)	170

Friction loss from sudden expansion of cross section

$$H_{fe} = \frac{\bar{V}_1^2}{2g}\left(1 - \frac{A_1}{A_2}\right)^2$$

Friction loss from sudden contraction of cross section

$$H_{fc} = \frac{\mathrm{K_C}\bar{V}_2^2}{2g}$$

Values of K_c are given on page 6–18, *Perry's Chemical Engineers' Handbook, 7th ed.*, Don W. Green, ed., McGraw-Hill Book Co., New York, NY, 1997.

Pipe friction (f) versus Reynolds number

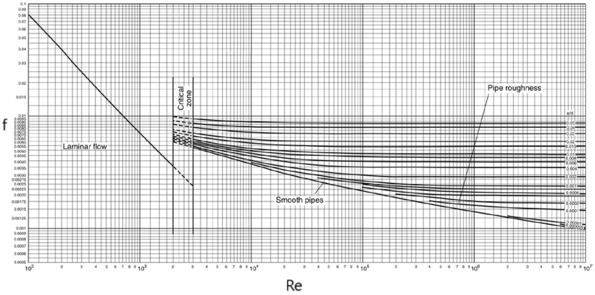


Figure 2. Graph from *Coulson and Richardson's Chemical Engineering volume 6, 3rd edition* pg 202.

Pressure drop in a pipe:

$$\Delta p_f = 8f\left(\frac{L}{d}\right)\frac{\rho_f V^2}{2}$$

Measurement of flowing fluids

Venturi meter

$$\sqrt{V_2^2 - V_1^2} = C_V\sqrt{\frac{2\,(p_1 - p_2)}{\rho_f}}$$

(V_2 is at throat of meter)

Orifice meter, design equation ($N_{Re} > 20{,}000$)

$$V = \frac{0.61}{\sqrt{1-\beta^4}}\sqrt{\frac{2\,(p_1 - p_2)}{\rho_f}}$$

Pilot tube, manometer measures ($p_s - P$)

$$v = C_p \sqrt{\frac{2\,(p_1 - p_2)}{\rho_f}}$$

Vessel configurations, dimensions and power

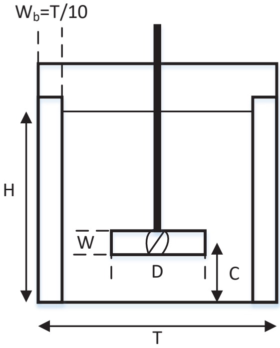


Figure 3. Stirred tank configuration.

Impeller diameter (D)/tank diameter (T): 0.3–0.5

Fill height (H)/tank diameter (T): 1 is typical for single impellers

Baffle width (W_b)/tank diameter (T): 0.1

Impeller clearance (C)/tank diameter (T): 0.2–0.3

The power drawn by the impeller power $= \rho_f P_o N^3 D^5$

P_o for 4 pitch blade turbine is 1.27, 5 for 6 blade Rushton, 0.6 for glassed steel 3 blade turbine

Powder flow

Flowability of a bulk solid is described by the ratio (ff_c) of consolidated stress (σ_1) to unconfined yield strength (σ_c), the behaviour can be defined by as follows:

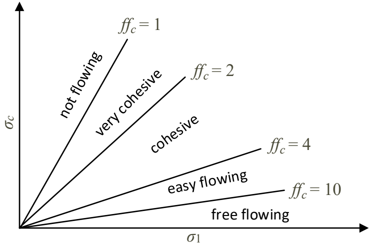


Figure 4. Powder flow function.

Notations

A = cross-sectional area, m^2

C_v, C_p = coefficients of velocity, dimensionless

D = diameter, m

g = acceleration of gravity = 9.807 $\mathrm{m/s}^2$

h_m = manometer reading, m

H_f = head loss due to friction, m

H_{fs} = head loss due to skin friction, m

H_{fc} = head loss due to contraction of cross-section, m

H_{fe} = head loss due to expansion of cross-section, m

K_e = expansion loss coefficient, dimensionless

K_c = contraction loss coefficient, dimensionless

L = length of pipe, m

N = the rotation rate, rps or rpm

P = pressure, $\mathrm{N/m}^2$

P_1 = upstream pressure, N/m^2

P_2 = downstream pressure, N/m^2

P_o = the power number dependent on N_{re}

$p_{1.}\ p_2$ = pressure in arms of manometer, N/m^2

p_s = stagnation pressure, N/m^2

V = fluid velocity, m/s

V_1 = upstream velocity, m/s

V_2 = downstream velocity, m/s

W_s = shaft work done by unit mass of fluid, J/kg

Z = elevation, m

α = kinetic energy correction factor, dimensionless

β = ratio of diameter of orifice to diameter of pipe, dimensionless

ρf = fluid density, kg/m^3

ρm = manometer fluid density, kg/m^3

ν = kinematic viscosity = μ/ρ, m^2/s

μ = viscosity, kg/m s

Heat transfer

Conduction

Fourier's Law (constant k)

steady state

$$q = \frac{-kA\Delta T}{\Delta x} = \frac{-\Delta T}{R}$$

unsteady state

$$\frac{\delta T}{\delta t} = \frac{k}{\rho C_p} x \frac{\delta^2 T}{\delta x^2}$$

Resistance in series

$$q = \frac{\Delta T}{\frac{x_A}{k_A A} + \frac{x_B}{k_B A} + \frac{x_C}{k_C A} + \cdots ..}$$

$$= \frac{\Delta T}{R_A + R_B + R_C + \cdots .}$$

Radial heat flow through a cylinder

$$q = \frac{2\pi k\, L\Delta T}{ln(r_o/r_i)}$$

Convection

$$q = hA\Delta T$$

where

$h = k'/\Delta x'$, heat transfer coefficient

k' = thermal conductivity of the fluid

$\Delta x'$ = thickness of the laminar film

Combined conduction and convection

$$q = UA_{\text{avg}}\ (\Delta T)$$

where

U = overall heat transfer coefficient

ΔT = overall temperature difference

$$\frac{1}{U} = \frac{A_r}{UA_r} = \frac{1}{h_i \frac{A_i}{A_r}} + \frac{x_m}{k_m \frac{A_m}{A_r}} + \frac{1}{h_o \frac{A_o}{A_r}} + \frac{1}{h_{Fi} \frac{A_i}{A_r}} + \frac{1}{h_{Fo} \frac{A_o}{A_r}}$$

where

A_r = reference area, usually the area of the solid through which heatis being conducted

h_{Fi}, h_{Fo} = inside and outside fouling factors

Radiation

$$q_{12} = \sigma AF\ (T_1^4 - T_2^4)$$

where

q_{12} = net radiation between surfaces 1 and 2, W

T_1, T_2 = absolute temperature of surfaces 1, 2, K

A = area of either surface, m^2

σ = Stefan-Boltzmann Constant

= 5.67 W/m2 K4

F = geometric view factor

Empirical dimensionless correlation

Turbulent flow in clean smooth pipes

$$\frac{h_i D}{k} = 0.023(N_{Re})^{0.8}(N_{Pr})^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14}\left[1+\left(\frac{D}{L}\right)^{0.7}\right]$$

where

N_{Re} = the Reynolds Number = DG/μ

N_{Pr} = the Prandtl Number = $C_p\mu/k$

Laminar flow in clean smooth pipes

$$\frac{h_i D}{k} = 1.86(N_{Re})^{0.33}(N_{Pr})^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14}\left(\frac{D}{L}\right)^{0.33}$$

where the Reynolds and Prandtl Numbers are as defined for turbulent flow.

Heat transfer to and from fluids flowing normal to a single tube

$$\frac{h_o \, {D_o}\big/{k_f}}{N_{Pr}^{0.3}} = 0.35 + 0.56(N_{Re})^{0.52}$$

where

N_{Re} = the Reynolds Number = $D_oG/\mu f$

The subscript f calls attention to the fact that the correlation is based on the mean film temperature, T_f, which is defined as the arithmetic mean of the average fluid temperature and the wall temperature.

Heat transfer to and from fluids flowing perpendicular to tube banks

$$\frac{h_{\text{avg}}\,D_o}{k_f} = b(N_{Re})^n$$

(b and n depend on geometry)

where

N_{Re} = the Reynolds Number = $DG_{\max}/\mu_f$

Heat transfer from condensing vapours

Vertical tubes

$$h_{\text{avg}} = 0.943\left[\frac{k_f^3\rho_f^2 g\lambda}{\Delta T_o L\mu_f}\right]^{0.25}$$

Horizontal tubes

$$h_{\text{avg}} = 0.725\left[\frac{k_f^3\rho_f^2 g\lambda}{\Delta T_o D_o\mu_f}\right]^{0.25}$$

Selected values for u

Hot fluid/ jacket	Cold fluid/ fluid in vessel	Shell and tube	Jacketed vessels (stainless steel)	Jacketed vessels (glass lined)
Steam	Water	1500–4000	850–1700	400–570
Steam	Light oils	300–900	340–910	230–425
Steam	Heavy oils	60–450	57–285	57–230

Hot fluid/ jacket	Cold fluid/ fluid in vessel	Shell and tube	Jacketed vessels (stainless steel)	Jacketed vessels (glass lined)
Brine	Water	250–750	230–1625	170–450
Brine	Organics	150–500	170–680	115–340

Overall heat transfer coefficient $U,\ W/(m^2K)$

Notation

A = area, $\mathrm{m^2}$

b = empirical constant

C_p = specific heat at constant pressure, $\mathrm{J/kg\ K}$

D = diameter, m

G = mass velocity, $\mathrm{kg/m^2\ s}$

G_{max} = mass velocity through minimum cross section in tube bundle

g = acceleration of gravity, 9.807 $\mathrm{m/s^2}$

h = heat transfer coefficient, $\mathrm{W/m^2\ K}$

k = thermal conductivity, $\mathrm{W/m\ K}$

L = length of tube or cylinder, m

q = heat flow per unit of time, W

R = heat transfer resistance, $\mathrm{m^2\ K/W}$

r = radius, m

T = temperature, K

t = time, s

U = over-all heat transfer coefficient, $\mathrm{W/m^2\ K}$

x = distance in direction of heat flow; thickness of layer, m

λ = latent heat of condensation or vaporisation $\mathrm{J/kg}$

μ = viscosity, $\mathrm{kg/m\ s}$

ρ = density, $\mathrm{kg/m^3}$

Subscripts

avg = average

f = film

i = inside

o = outside

r = reference

w = wall

m = mean or log mean

Distillation

Flash (or equilibrium) distillation

$Fz_F = yV + xL$ (component material balance)

$F = V + L$ (overall material balance)

Differential (simple or Rayleigh) distillation

$$\ln \frac{W}{W_o} = \int_{x_o}^{x} \frac{dx}{y - x}$$

When the relative volatility α is constant $y = \alpha x/[1 + (\alpha - 1)x]$ can be substituted to give

$$\ln \frac{W}{W_o} = \frac{1}{(\alpha - 1)} \ln \left[\frac{x(1 - x_o)}{x_o(1 - x)} \right] + ln \left[\frac{1 - x_o}{1 - x} \right]$$

For binary system following Raoult's Law

$$\alpha = \frac{\left({}^{y}/_{x} \right)_a}{\left({}^{y}/_{x} \right)_a} = \frac{p_a}{p_b}$$

where

p_i = partial pressure of component i

Continuous distillation (binary system) where constant molal overflow is assumed

Total material balance

$$F = D + B$$

$$Fz_F = Dx_D + Bx_B$$

Operating lines

Rectifying section

Total material: $V_{n+1} = L_n + D$

Component A: $V_{n+1}\, y_{n+1} = L_n x_n + D x_D$

$$y_{n+1} = \frac{L_n}{L_n + D} x_n + \frac{D x_D}{L_n + D}$$

Stripping section

Total material: $L_m = V_{m+1} + B$

Component A: $L_{m+1}\, x_m = V_{m+1}\, y_{m+1} + B x_B$

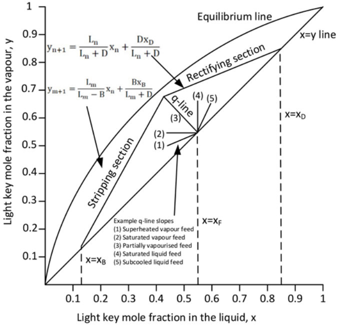
$$y_{m+1} = \frac{L_m}{L_m - B} x_m - \frac{B x_b}{L_m - B}$$

Reflux ratio

Ratio of reflux to overhead product

$$R_D = \frac{L}{D} = \frac{V - D}{D}$$

Graphical representation of operating lines, equilibrium lines and feedlines



Murphree Plate Efficiency

$$E_{ME} = \frac{y_n - y_{n+1}}{y_n^* - y_{n+1}}$$

where

y_n = concentration of vapour above plate n

y_{n+1} = concentration of vapour entering from plate below n

y_n^* = concentration of vapour in equilibrium with liquid leaving plate n

Notation

α = relative volatility

B = moles of bottoms product

D = moles of overhead product

F = moles of feed

L = molar liquid downflow

R_D = ratio of reflux to overhead product

V = molar vapour upflow

W = weight in still pot

x = mole fraction of the more volatile component in the liquid phase

y = mole fraction of the more volatile component in the vapour phase

z_D = mole fraction of the more volatile component

Subscripts

B = bottoms product

D = overhead product

F = feed

m = any plate in stripping section of column

$m+1$ = plate below plate m

n = any plate in stripping section of column

$n+1$ = plate below plate n

o = original charge in still pot

Mass Transfer

Diffusion

Molecular diffusion

$$\frac{N_A}{N} = \frac{P_A}{p}\left[\frac{N_A}{A} + \frac{N_B}{A}\right] - \frac{D}{RT}\frac{\delta p_a}{\delta z}$$

Unidirectional diffusion of a gas A through a second stagnant gas B $(N_B = 0)$

$$\frac{N_A}{A} = \frac{-DP}{RT(p_B)_{lm}}\ x\ \frac{(p_{A2} - p_{A1})}{z_2 - z_1}$$

in which $(p_B)_{lm}$ is the log mean of P_{B2} and P_{B1}

Equimolar countercurrent diffusion ($N_B = -N_A$) (gases)

$$\frac{N_A}{A} = \frac{-D}{RT}\ x\ \frac{(p_{A2} - p_{A1})}{z_2 - z_1}$$

Unsteady state diffusion

$$\frac{\partial p_A}{\partial t} = D\,\frac{\partial^2 p_A}{\partial z^2}$$

Convection

Two-film theory

$$\frac{N_A}{A} = k_G(p_{AG} - p_{Ai}) = k_L(C_{Ai} - C_{AL})$$

$$= K_G(p_{AG} - p_A^*) = K_L(C_A^* - C_{AL})$$

Overall coefficients

$$\frac{1}{K_G} = \frac{1}{k_G} + \frac{H}{k_L}$$

$$\frac{1}{K_L} = \frac{1}{Hk_G} + \frac{1}{k_L}$$

Transfer unit

HTU – height of a transfer unit

$$H_{TG} = \frac{G}{K_G a}$$

$$H_{TL} = \frac{L}{K_L a}$$

NTU – number of transfer units

$$N_{TG} = \int_{y1}^{y2} \frac{dy}{y^* - y} + \frac{1}{2}\ln\frac{1 - y_2}{1 - y_1}$$

$$N_{TL} = \int_{x1}^{x2} \frac{dx}{x - x^*} + \frac{1}{2}\ln\frac{1 - x_1}{1 - x_2}$$

For dilute solutions (straight operating and equilibrium line)

$$N_{TG} = \frac{y_1 - y_2}{(y - y^*)_{lm}}$$

$Z = N_{TG}\, H_{TG} = N_{TL}\, H_{TL} =$ tower height

Dimensionless group equation (Sherwood)

$$(N_{sh}) = 0.023\ (N_{Re})^{0.8}\ (N_{Sc})^{1/3}$$

Momentum, heat and mass transfer analogy

$$0.5f = j_H = j_D$$

where

f = Fanning friction factor

$$j_H = \frac{h}{C_p G}\left[\frac{C_p \mu}{k}\right]^{0.667} \left[\frac{\mu_w}{\mu}\right]^{0.14}$$

$$j_M = \frac{k_c}{G}(N_{Sc})^{0.667}$$

Notation

A = area perpendicular to direction of diffusion
a = interfacial area per unit volume, $\mathrm{m^2/m^3}$
C = concentration in liquid phase
d = tube diameter
D = molecular diffusivity, $\mathrm{m^2/s}$
G = gas mass velocity, mass (time) (area)
H = Henry's Law constant, $p_i = HC_i$
h = heat transfer coefficient, $\mathrm{W/m^2\ K}$
k = film coefficient of mass transfer
K = overall coefficient of mass transfer
L = liquid mass velocity, mass/(time)(area)
N = moles of a substance per unit time
p = partial pressure
P = total pressure
R = gas constant
N_{Re} = Reynolds number = $du\rho/\mu$
N_{Sc} = Schmidt number = $\mu/\rho D$

N_{Sh} = Sherwood number = kd/D
t = time
T = absolute temperature
u = velocity
lm = logarithm mean average

Greek Letters

ρ = density
μ = viscosity

Subscripts

A, B = components of mixture
B = gas phase
L = liquid phase
i = interface
x = mole fraction of liquid
y = mole fraction of gas
z = length in direction of travel
$*$ = equilibrium concentration

Thermodynamics

Definitions

System – an arbitrarily chosen portion of space which is under consideration.

- Closed system – one in which matter does not pass through its boundaries.
- Open system – one in which matter flows across its boundaries.
- Isolated system – one in which there is no interchange of energy or matter with the surroundings.

Boundaries – the envelope separating the system from the surroundings.

Universe – a system and its surroundings.

Total energy, E – the sum of the various forms of energy of the system: eg U, internal energy; E_k, kinetic energy; E_p, potential energy; hence,

$$E = U + E_p + E_k + \ldots\ldots$$

First law

In an isolated system

$$\Delta E = E_2 - E_1 = 0$$

In a closed system

$$\Delta E = Q - W$$

In an open system

$$\Delta E + \Sigma(H + E_p + E_k) = Q - W$$

where the summed terms refer to leaving (+) and entering (–) streams

In a steady state open system

$$\Delta E_{\text{system}} = 0$$

Hence for the entering and leaving streams

$$\Delta H + \Delta E_k + \Delta E_p = Q - W$$

Second law

For any real process the total entropy of the universe always increases

$$\Delta S_{\text{system}} + \Delta S_{\text{surroundings}} > 0$$

Thermodynamic functions: definitions and relationships

Definition of entropy

$$\Delta S = \int \frac{dQ_{rev}}{T}$$

From first and second laws, with changes in E_k, E_p, and composition negligible,

$$dU = dQ_{\text{rev}} - PdV = TdS - PdV$$

also

$$dH = dU + d\,(PV) = TdS + VdP$$

$$dG = dH - d\,(TS) = -\,SdT + VdP$$

$$dA = dU - d\,(TS) = -\,SdT - PdV$$

$$C_p = (\delta H/\delta T)_p;\ C_v = (\delta U/\delta T)_v;\ \gamma = (C_p/C_v)$$

P, V, T, S, U, H, G, A are state functions. Q and W are path functions and have no total derivatives.

Perfect-gas relationships

For any path

$$\Delta H = \int_{T1}^{T2} C_p \, dT \qquad \text{or} \qquad (\delta H/\delta P)_T = 0$$

For any path

$$\Delta H = \int_{T1}^{T2} C_v \, dT \qquad \text{or} \qquad (\delta U/\delta V)_T = 0$$

For monoatomic gas

$$C_p = 2.5\,R \qquad \text{and} \qquad C_v = 1.5\,R$$

For diatomic gas

$$C_p = 3.5\,R \qquad \text{and} \qquad C_v = 2.5\,R$$

Adiabatic ($Q = 0$) and reversible path for system with $\Delta E_p = \Delta E_k = 0$

$$(P_2/P_1) = (V_1/V_2)^{\gamma} = (T_2/T_2)^{\gamma/(\gamma-1)}$$

$$W_{\text{nonflow}} = \Delta U = \frac{-RT_1}{\gamma - 1}\left[\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma} - 1\right] \qquad \text{(per mole)}$$

$$W_{\text{flow}} = \Delta H = \gamma[W_{\text{nonflow}}] \qquad \text{(per mole)}$$

Isothermal path, flow or nonflow

$$\frac{P_2}{P_1} = \frac{V_1}{V_2}$$

$$W = RT \ln \frac{V_2}{V_1} = RT \ln \frac{P_1}{P_2} \qquad \text{(per mole)}$$

Criteria for equilibrium change

For system and surroundings

$$dS_{\text{universe}} = 0$$

For system alone

$$dG = 0 \text{ when } P, T = \text{constant}$$

$$dA = 0 \text{ when } V, T = \text{constant}$$

Chemical thermodynamics

Fugacity (f) and Activity (a)

$$\Delta G = RT \ln\left({}^{f_2}/_{f_1}\right) = \int_1^2 V\,dP \qquad \text{(per mole)}$$

(constant-temperature path)

and the limit of f/P as P approaches $0 = 1.00$

$$a = f/f_o$$

Equilibrium

Standard free energy at temperature T for the reaction

$$aA + bB \rightleftharpoons rR + sS$$

$$\Delta G^o = rG_R^o + sG_S^o - aG_A^o - bG_B^o = RT \ln \frac{a_R^r a_S^s}{a_A^a a_B^b} = -RT \ln K_a$$

Cells

At standard conditions

$$\Delta G^\circ = -\varepsilon^\circ nF = -RT \ln K_a$$

At actual conditions

$$G = \varepsilon nF = \varepsilon^{\circ} nF - RT\ln\frac{a_R^r a_S^s}{a_A^a a_B^b}$$

Thermodynamic models

Model	Selection parameters
Peng-Robinson (PR), Soave-Redlich-Kwong (SRK), API	Gases, non polar
e-NTRL, Pitzer, Bromley, e-UNIQUAC, e-UNIFAC	Electrolytes, Enthalpic deviation
SAFT, Lattice-Fluid	Electrolytes, Entropic deviation
NRTL, UNIQUAC, Wilson, UNIFAC	Polar, non electrolyte, <10bar
PR, SRK,	Polar, non electrolyte, >10bar

H–S

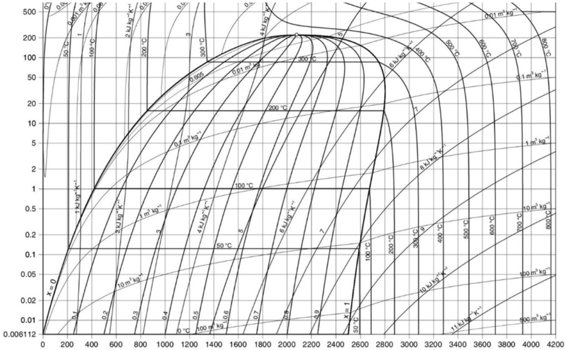


Figure 6. Logarithmic pressure (P-bar)-specific enthalpy ($h - kJ\ kg^{-1}$) diagram with lines of constant specific entropy, temperature and specific volume by W. Wagner, H.J. Kretzschmar, *International Steam Tables 2nd edition* pg 350.

Notation

$A = U - TS$, Helmholtz work function
a = activity
C = heat capacity
E = total energy of the system
E_k = kinetic energy of the system
E_p = potential energy of the system
ε = reversible voltage of cell
F = faradays per equivalent
f = fugacity
$G = H - TS$, Gibbs free energy
$H = U + PV$, enthalpy
K = equilibrium constant for the reaction as written
K_a = equilibrium constant in terms of activity
K_f = equilibrium constant in terms of fugacity
K_p = equilibrium constant in terms of partial pressure
n = number of equivalents for the reaction as written
P = pressure
Q = heat, defined as positive when absorbed by system
R = gas constant
S = entropy
T = absolute temperature
U = internal energy of the system
V = volume
W = work, defined as positive when done by system on surroundings
Δ = final state minus initial state
$\gamma = (C_p/C_v)$

Superscript

$^\circ$ = standard state

Kinetics and reactor design

Rate of reaction

The rate of reaction of any component A based on unit volume of fluid is

$$r_A = \frac{1}{V}\frac{dN_a}{dt}$$

and where density remains unchanged

$$r_A = \frac{dC_A}{dt}$$

Frequently, the rate can be described as a temperature-dependent term times a concentration-dependent term, or

$$r_A = kf\ (C_A, C_B \ldots\ldots)$$

Order, molecularity, elementary reactions

Where the rate can be expressed as

$$-r_A = kC_A^a C_B^b \ldots$$

the reaction is ath order with respect to A and nth order overall; $n = a + b + \ldots$

Note: a, b, $\ldots$ are empirically observed and are not necessarily equal to the stoichiometric coefficients. In the special case where a, b, $\ldots$ are the stoichiometric coefficients, the reaction is elementary: unimolecular ($n = 1$), bimolecular ($n = 2$), trimolecular ($n = 3$).

Rate constant k and temperature dependency of a reaction

$$k = (\text{conc})^{1-n}(\text{time})^{-1}$$

From Arrhenius's Law the variation with temperature is

$$k = k_o e^{-E/RT} \qquad \text{or}$$

$$\ln \frac{k_2}{k_1} = \frac{E}{R}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]$$

where E is the activation energy of the reaction.

Homogeneous, constant fluid density, batch kinetics

Irreversible first-order reaction

For the reaction $A \longrightarrow$ products, with rate

$$-\frac{dC_A}{dt} = kC_A \quad \text{or} \quad \frac{dX_A}{dt} = k(1 - X_A)$$

the integrated form is

$$-\ln \frac{C_A}{C_{AO}} = -\ln(1 - X_A) = kt$$

Irreversible second-order reaction

For the reaction $A + B \longrightarrow$ products, with rate

$$-\frac{dC_A}{dt} = kC_A C_B$$

When $M = {}^{C_{BO}}\!/_{C_{AO}} \neq 1$, the integrated form is

$$\ln \frac{C_B C_{AO}}{C_{BO} C_A} = \ln \frac{M - X_A}{M(1 - X_A)} = (C_{BO} - C_{AO})kt$$

When $C_{A0} = C_{B0}$, the integrated form is

$$\frac{1}{C_A} - \frac{1}{C_{A0}} = \frac{1}{C_{A0}}\frac{X_A}{1 - X_A} = kt$$

Irreversible nth-order reaction

For the reaction with rate

$$-\frac{dC_A}{dt} = kC_A^n$$

the integrated form for $n \neq 1$ is

$$C_A^{1-n} - C_{A0}^{1-n} = (n-1)kt$$

Reversible first-order reaction

For the reaction $A \underset{2}{\overset{1}{\rightleftharpoons}} R,\ K = k_1/k_2$ with rate

$$-\frac{dC_A}{dt} = \frac{dC_R}{dt}\ k_1C_A - k_2C_R$$

the integrated form is

$$-\ln\frac{X_{Ae} - X_A}{X_{Ae}} = -\ln\frac{C_A - C_{Ae}}{C_{A0} - C_{Ae}} = (k_1 + k_2)t$$

Integration of rate in general

For the reaction with rate

$$-r_A = -\frac{dC_A}{dt} = kf(C_A, C_B, \ldots)$$

$$t = C_{A0}\int_0^{X_A}\frac{dX_A}{(-r_A)} = \int_{C_{A0}}^{C_A}\frac{dC_A}{kf(C_A, C_B, \ldots)}$$

which is to be solved analytically or graphically.

Batch reaction with changing fluid density

Where density change is proportional to the fractional conversion of any reactant A (isothermal systems),

$$\frac{C_A}{C_{A0}} = \frac{1 - X_A}{1 + \varepsilon_A X_A}$$

where

$$\varepsilon_A = \frac{V_{X_{A-1}} - V_{X_{A-0}}}{V_{X_{A-0}}}$$

The rate for any reactant A is then

$$-r_A = -\frac{1}{V}\frac{dN_A}{dt} = \frac{C_{A0}}{(1 + \varepsilon_A X_A)}\frac{dX_A}{dt} = kf\,(C_A, C_B, \dots)$$

Integrating in the general case

$$t = C_{A0}\int_0^{X_A} \frac{dX_A}{(1 + \varepsilon_A X_A)(-r_A)}$$

Flow reactors

Capacity measures

Space time: $\tau =$ time required to process one reactor volume of entering feed = mean residence time

$$\tau = \frac{V}{v} = \frac{VC_{A0}}{F_{AO}} \qquad \text{(units of time)}$$

Design equation for plug flow (ideal tubular) reactor

In general

$$\tau = C_{A0} \int_0^{X_A} \frac{dX_A}{-r_A}$$

or

$$\frac{V}{F_{A0}} = \int_0^{X_A} \frac{dX_A}{(-r_A)}$$

For irreversible first-order reactions (isothermal)

$$-k\tau = (1 + \epsilon_A) \ln(1 - X_A) + \epsilon_A X_A$$

For reversible first-order reactions

$A \underset{2}{\overset{1}{\rightleftharpoons}} rR$ (isothermal)

$$-k_1\tau = \frac{\epsilon_A X_A}{N} + \frac{N + \epsilon_A}{N^2} \ln(1 - N X_A)$$

where

$$N = 1 + \frac{k_2}{k_2}(1 + \epsilon_A)$$

Design equation for back-mix (ideal stirred tank) reactor

$$\tau = \frac{C_{A0} X_A}{(-r_A)}$$

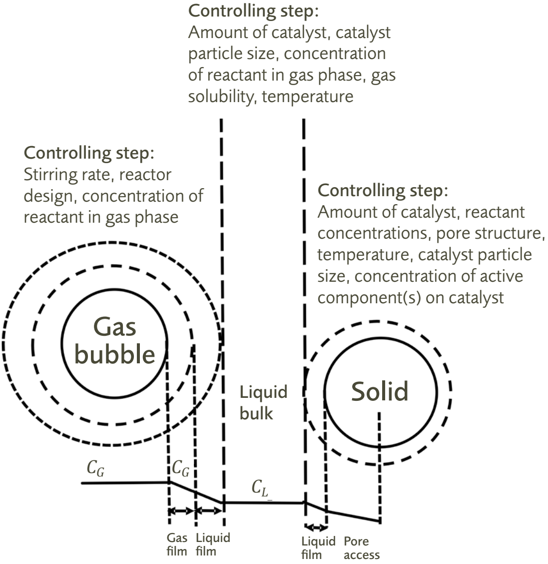
or

$$\frac{V}{F_{A0}} = \frac{X_A}{(-r_A)}$$

For a first-order reaction in j equal-sized backmix reactors in series

$$\frac{C_A\text{entering}}{C_B\text{leaving}} = (1 + k\tau \text{ per reactor})^j$$

Variables affecting reaction rate



Controlling step:
Amount of catalyst, catalyst particle size, concentration of reactant in gas phase, gas solubility, temperature

Controlling step:
Stirring rate, reactor design, concentration of reactant in gas phase

Controlling step:
Amount of catalyst, reactant concentrations, pore structure, temperature, catalyst particle size, concentration of active component(s) on catalyst

Residence time distribution in multistage continuous stirred tank reactors (CSTR)

$$E(t_r) = \frac{n^n}{(n-1)!} t_r^{n-1} e^{-nt_r}$$

where n is the number of stages in CSTR, t_r is the time/mean residence time.

Segregation model

Models the real reactor as a number of small batch reactors, each spending a different time in the reactor. The mean conversion is

$$\bar{X} = \int_0^\infty X(t)\,E(t)$$

For first order reaction the conversion-time relationship is $X(t=1-e^{-kt}$ and $E(t)$ is the residence time distribution.

Notation

A, B, R, etc = substance A etc.

a, b, ... = exponents on concentration term of empirical rate expression

C_A = concentration of A, moles A/volume

C_{A0} = initial concentration of A, moles A/volume

F_{A0} = feed rate of A or flow rate of A entering the reactor, moles A/time

K = equilibrium constant

k = reaction rate constant, (conc^{1-n}) (time^{-1})

n = order of reaction

N_A = moles of A

r_A = rate of reaction of any component A, moles A formed/time-volume

T = temperature

t = time

V = volume of fluid in batch reactor, volume of fluid in a flow reactor, or reactor volume

v = volumetric feed rate, volume of feed/time

X_A = fraction of reactant A converted, dimensionless

Greek symbols

ϵ_A = measure of density change with reaction, dimensionless

τ = space time based on entering feed, time

Subscripts

e = equilibrium value

Filtration and cake washing

Filtration

Darcy's law applied to constant pressure filtration

$$\Delta P = \frac{\mu c a}{A^2} V \frac{dV}{dt} + \frac{\mu L_m}{A K_m} \frac{dV}{dt}$$

The first terms refers to the pressure across the cake and the second across the medium (m).

Cake washing

Washing by displacement in cakes (formation of cake and continuous addition of water)

$$\frac{C}{C_o} = 0.5 \left[1 + erf \left(\frac{1-n}{2n^{1/2}} Pe_c^{1/2} \right) \right]$$

where Pe_c is

$$Pe_c = \frac{uL}{D_L}$$

Washing by reslurry of cake (suspension of cake followed by cake filtration and repeated until the last traces are removed)

$$\frac{C_s - C_w}{C_o - C_w} = \frac{1}{[1 + (V_w / z V_m)]^z}$$

Washing by successive dilution/cross flow filtration (solids are in continuous suspension and equal amounts of water are added and removed)

$$C = C_w \left[1 - \left(1 - \frac{C_o}{C_w} \right) exp \left(\frac{-JAt}{V} \right) \right]$$

Notation

A = area $\mathrm{m^2}$

C_o = initial concentration $\mathrm{g\ L^{-1}}$

C_S = solute concentration in wash water $\mathrm{g\ L^{-1}}$

C_w = concentration of wash liquor $\mathrm{g\ L^{-1}}$

c = dry mass of solids per unit filtrate volume $\mathrm{kg\ m^{-3}}$

D_L = axial dispersion coefficient $\mathrm{m^2\ s^{-1}}$

J = flux rate $\mathrm{m^3\ m^2\ s^{-1}}$

K = kozeny constant

L = bed thickness m

n = wash ratio

Pe_c = peclet number

t = time s

u = average interstitial wash velocity $\mathrm{m\ s^{-1}}$

V = volume of filtrate $\mathrm{m^3}$

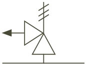
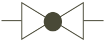
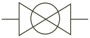
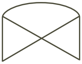
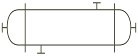
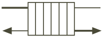
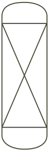
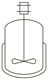
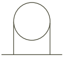
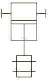
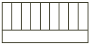
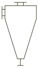
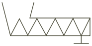
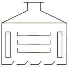
V_m = volume of residual liquor in saturated cake $\mathrm{m^3}$

Z = number of satges

α = local specific cake resistance $\mathrm{m\ kg^{-1}}$

μ = liquid viscosity $\mathrm{Pa\ s}$

Graphical symbols for general engineering

Relief (angle pressure)		Check (non return or reflux)	
Globe		Ball	
Needle		Diaphragm	
Heat exchanger		Shell and tube	
Plate type		Cooling tower	
Tray column		Fluid contacting vessel	
Autoclave		Storage sphere	
Centrifugal pump		Positive displacement pump	
Filter press		cyclone	
Screw feeder		Drying oven	

Selected hazard identification methods

Hazard identification method	Basic scope
Hazard study 1	Identification of materials being used or produced. Potential hazards that cause fire, explosion, toxic and environmental impact. Review of previous incidences. Regulatory issues.
Hazard study 2	Systematic study of significant hazards in order to establish knowledge of the main hazard such as fire, explosion, harmful exposure, pollution, major financial effects and operability problems at the early stage.
Hazard study 3 (Hazop)	To identify and evaluate hazards at the detail design phase of the project that impact safety, operability, quality and maintenance.
Hazard study 4/5	To verify that the plant/process has been built as designed and all actions from the previous hazard studies are completed. Certification, operating and maintenance instructions are in hand. Confirmation of compliance with company and legislative standards.
Hazard study 6	To ensure the safety developed at the design phase is still appropriate after a few months of production.
What-if	Identification of hazards by applying 'what if' scenario.
Human error	Identification of human failures that could be made in task.
Fault tree analysis	Graphical view of causes and effects by structuring the consequence back to the cause.
LOPA	To assess the adequacy of the independent layers of protection for high consequence scenarios.

Conversion factors

Acceleration	
1 m/s^2	= 3.281 ft/s^2 = 2.237 (mile/hr)/s = 3.600 km/hr–s
1 rev/s^2	= 3600 rev/min^2 = 6.283 rad/s^2
Angle	
1 rad	= 1/2π circle = 0.1592 rev = 0.637 quad = 57.3 deg = 3,438 min = 2.063 x 10^{5}s
Density	
1 kg/m^3	= 0.06243 lb$_m$/cu ft = 3.613 x 10^{-5} lb$_m$/cu in = 1.000 x 10^{-3} g/cc
Flow (volumetric)	
1 m^3/s	= 2119 cu ft/min = 13200 UK gal/min = 15850 US gal/min
Length	
1 m	= 3.281 ft = 6.214 x 10^{-4} mile = 1.094 yd = 39.37 in = 1 x 10^6 microns (μ) = 1 x 10^{10}Å

Mass	
1 kg	= 2.205lb$_m$ = 9.84 x 10^{-4} long ton = 1.543 x 10^4 grain = 1 x 10^{-3} metric tonne = 1 x 10^3g = 0.06852 slug = 0.01968 cwt
Pressure	
1 N/m^2	= 1.450 x 10^{-4}1b$_f$/in^2 = 9.869 x 10^{-6}atm = 1 x 10^{-5} bar = 7.5 x 10^{-3} mm Hg @ 0°C = 7.5 x 10^{-3} torr = 3.345 x 10^{-4} ft H_2O @ 0°C = 1.0197 x 10^{-5}kg$_f$/cm^2
Power	
1 W	= 0.7376 ft lb$_f$/s = 1.360 x 10^{-3} hp (metric) = 0.8598 kcal/hr = 3.412 Btu/hr
Temperature	
°F	= 1.8 (°C) + 32
K	= °C + 273
°R	= °F + 459
Time	
1 nanosecond	= 1 x 10^{-9}s

Velocity	
1 m/s	= 3.281 ft/s = 0.03728 mile/min = 2.237 mile/hr = 3.600 km/hr
1 rev/min	= 0.1047 rad/s = 6 deg/s
Viscosity	
1 kg/ms	= 1 Pa-s = 1000 centipoise = 10 g/cm–s (poise) = 0.6720 lb$_m$/ft–s = 2420 lb$_m$/ft–hr
Volume	
1 m^3	= 35.31 ft^3 = 1.308 yd^3 = 6.102 x 10^4 in^3 = 1000 litres
Work and energy	
1 J	= 9.478 x 10^{-4} Btu = 2.778 x 10^{-4} kW–hr = 3.777 x 10^{-7} hp–hr (metric) = 2.388 x 10^{-4} kcal = 0.2388 cal = 2.778 x 10^{-4} W–hr = 9.869 x 10^{-3} litre–atm = 0.7376 ft-lb$_f$ = 3.485 x 10^{-4} ft^3–atm = 1 x 10^7 ergs

Mole fraction (x) to mass fraction (w)

$$w_A = \frac{x_A M_A}{x_A M_A + x_B M_B}$$

Mass fraction (w) to mole fraction (x)

$$x_A = \frac{w_A/M_A}{w_A/M_A + w_B/M_B}$$

where

$M_i =$ molecular weight of i

Physical constants

Gas constants

$$
\begin{aligned}
R &= 0.0821 \text{ atm-litre/g-mole-K} \\
&= 1.987 \text{ g-cal/g-mole-K} \\
&= 1.987 \text{ Btu/lb}_m\text{-mole-°R} \\
&= 8.314 \text{ joules/g-mole-K} \\
&= 1546 \text{ ft-lbf /lb}_m\text{-mole-°R} \\
&= 10.73 \text{ (psi)-ft 3/lb}_m\text{-mole-°R} \\
&= 0.7302 \text{ atm-ft 3/lb}_m\text{-mole-°R}
\end{aligned}
$$

Acceleration of gravity (standard)

$$g = 9.807 \text{ m/s}^2$$

Avogadro's number

$$N = 6.023 \text{ x } 10^{23} \text{ molecules/mole}$$

Boltzmann's constant

$$K = 1.387 \text{ x } 10^{-23} \text{ J/K}$$

Planck's constant

$$h = 6.626 \text{ x } 10^{-34} \text{J–s}$$

Stefan-Boltzmann constant

$$
\begin{aligned}
\sigma &= 5.67 \text{ x } 10^{-8} \text{ W/m}^2\text{K}^4 \\
&= 1.712 \text{ x } 10^{-9} \text{ Btu/hr–sq ft–°R}^4
\end{aligned}
$$

Velocity of light

$$c = 3 \text{ x } 10^8 \text{ m/s} = 186{,}000 \text{ mile/s}$$

Velocity of sound in dry air, 0°C and 1 atm

$$= 331.4 \text{ m/s}$$

Heat of fusion of water at 1 atm, 0°C

$$= 334 \text{ kJ/kg}$$

Heat of vaporisation of water at 1 atm, 100°C

$$= 2257.6 \text{ kJ/kg}$$

1 lb-mole of perfect gas occupies 359 cu ft at standard conditions (32°F, 14.7 lb force/sq in abs)

1 mole of perfect gas occupies 22.4 litres at 0°C and 760 mm Hg

Thermochemistry

F = 96,500 coulombs/gram equivalent

joules = volts x coulombs

coulombs = amperes x seconds

Dimensionless groups

Name	Symbol	Formula
Fanning friction factor	f	$\Delta pd/2L\rho V^2$
Heat transfer factor	j_H	$(h/c_pG)(c_p\mu/k)^{2/3}$
Mass transfer factor	j_M	$(k_c\rho/G)(\mu/\rho D)^{2/3}$
Froude number	N_{Fr}	V^2/gL
Graetz number	N_{Gz}	wc_p/kL
Grashof number	N_{Gr}	$L^3\rho^2\beta g\Delta T/\mu^2$

Name	Symbol	Formula
Nusselt number	N_{Nu}	hd/k
Peclet number	N_{Pe}	$LV\rho c_p/k$
Power number	N_{Po}	$P/\rho n^3 d^5$
Prandtl number	N_{Pr}	$c_p\mu/k$
Reynolds number in pipes (di-ameter pipe)	N_{Re}	$dV\rho/\mu$
Schmidt number	N_{Sc}	$\mu/\rho D$
Sherwood number	N_{Sh}	$k_c L/D$

Notation

c_p = specific heat, $\mathrm{J/kg\ K}$
D = molecular diffusivity, $\mathrm{m^2/s}$
d = diameter, m
G = mass velocity, $\mathrm{kg/m^2\ s}$
g = acceleration of gravity, $9.807\ \mathrm{m/s^2}$
h = heat transfer coefficient, $\mathrm{W/m^2\ K}$
k = thermal conductivity, $\mathrm{W/m\ K}$
k_c = mass transfer coefficient, $\mathrm{m/s}$
L = characteristic dimension, m
N = rate of rotation, $\mathrm{s^{-1}}$
P = power to agitator, W
p = pressure, $\mathrm{N/m^2}$
T = temperature, K
V = fluid velocity, $\mathrm{m/s}$
w = mass flow rate, $\mathrm{kg/s}$
β = coefficient of bulk expansion, $\mathrm{K^{-1}}$
ρ = density, $\mathrm{kg/m^3}$
μ = viscosity $\mathrm{kg/m\ s}$

Abbreviations

atm = atmosphere
Btu = British thermal unit
cal = calorie
cm = centimetre
cu = cubic
ft = foot, feet
g = gram
hp = horsepower
hr = hour
in = inch
kg = kilogram
km = kilometre
kW = kilowatt
lb_m = pound-mass
lb_f = pound-force
m = metre
min = minute
quad = quadrant
°R = degrees Rankine
rad = radian
rev = revolution
s = second
yd = yard
µ = micron

Greek alphabet

Α, α	alpha
Β, β	beta
Γ, γ	gamma
Δ, δ	delta
Ε, ε	epsilon
Ζ, ζ	zeta
Η, η	eta
Θ, θ	theta
Ι, ι	iota
Κ, κ	kappa
Λ, λ	lambda
Μ, μ	mu
Ν, ν	nu
Ξ, ξ	xi
Ο, ο	omicron
Π, π	pi
Ρ, ρ	rho
Σ, σ	sigma
Τ, τ	tau
Υ, υ	upsilon
Φ, φ	phi
Χ, χ	chi
Ψ, ψ	psi
Ω, ω	omega

Mathematics

$$a^2 - b^2 = (a + b)(a - b)$$

$$a^3 + b^3 = (a + b)(a^2 - ab + b^2)$$

$$a^3 - b^3 = (a - b)(a^2 + ab + b^2)$$

$$ax^2 + bx + c = 0 \quad x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Area of circle $= \pi r^2$

Circumference of circle $= 2\pi r$

Surface of sphere $= 4\pi r^2$

Volume of sphere $= (4/3)\pi r^3$

Volume of cone or pyramid $= 1/3$ (base) (height)

$$dax = adx$$

$$dx^n = nx^{n-1}\,dx$$

$$d(u + v) = du + dv$$

$$d(uv) = udv + vdu$$

$$d\left[\frac{u}{v}\right] = \frac{vdu - udv}{v^2}$$

$$de^{ax} = ae^{ax}dx$$

$$da^x = a^x \log_e a \, dx$$

$$d \sin x = \cos x \, dx$$

$$d \cos x = - \sin x \, dx$$

$$d \tan x = \sec^2 x \, dx$$

$$\int (u+v)dx = \int u dx + \int v dx$$

$$\int u dv = uv - \int v du$$

$$\int x^n dx = {x^{n+1}}/{(n+1)} \quad \text{for n} \neq \text{-1}$$

$$\int \frac{dx}{x} = \log_e x = \log_e (ln\, x)$$

$$\int e^{ax} dx = \frac{e^{ax}}{a}$$

Binomial series

$$(x+y)^n = x^n + nx^{n-1}y + \frac{n(n-1)}{2!}$$

$$x^{n-2}y^2 + \cdots (y^2 < x^2)$$

Taylor series

$$f(x) = f(a) + f^{'}(a)\frac{x-a}{1!} + f^{''}(a)\frac{(x-a)^2}{2!} + \cdots$$

MacLaurin series

$$f(x) = f(0) + f^{'}(0)\frac{x}{1!} + f^{''}(0)\frac{x^2}{2!} + \cdots$$

Exponential series

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$$

$$\pi = 3.1416,\ e = 2.71828,\ i = \sqrt{-1},\ i^2 = -1,\ i^4 = 1$$

Arithmetic mean

$$\frac{a+b}{2}$$

Geometric mean

$$\sqrt{ab}$$

Harmonic mean

$$\frac{2ab}{a+b}$$

Logarithmic mean

$$\frac{a-b}{\ln {}^{a}/_{b}}$$

Solution of

$$\frac{dy}{dx} + Py = Q$$

where P, Q are constants or functions of x

Integrating factor = $e^{\int P dx} = IF$

Solution = $y \text{ x } IF = \int (IF \times Q) dx + C$

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Connect you to our globally diverse community of chemical, biochemical and process engineers

Support you to be at the heart of a sustainable future which benefits you, society and the environment

Recognise and **represent** your voice and the profession on a local, national and global stage

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