Nomenclature – Unit operations

-Typical units are given, always make sure the units are consistent with other values/properties and equation.
-Flow rate (mol/s) and flux (mol/s·m^2) often use the same letter and terminology, depends on the equation and material balance.

MODULE 1 - DRYERS

Humid air = dry air + water = air water mixture = total

a: Specific surface of the bed [m^2 surface area /m^3 bed]
a: Slope of drying rate in falling-rate period ($R = aX$)
A: Surface area of drying solid [m^2]
c: Heat capacity [kJ/kg·K]
c_S: Humid heat of air-water mixture [kJ/kg dry air·K]

$$c_S = 1.005 + 1.88H$$

D_L: Liquid diffusion coefficient [m^2/h]
D_p: Particle diameter [m], Equivalent diameter of a sphere witht the same area [m]
G: Mass flow rate of dry air [kg dry air/h] (≡ *inert* mass flow rate: G') **(Continuous dryer)**
G: Mass flow rate of dry air/cross-section (≡ Mass flux) [kg dry air/h·m^2] (≡ *inert*: G') **(Batch dryer)**

$$G = v\rho\left(\frac{1}{1+H}\right)$$

G_t: Mass velocity of humid air/cross-section (≡ Mass flux) [kg/h·m^2] **(Batch dryer)**

$$G_t = v\rho$$

h, h_c: Convective heat transfer coefficient [W/m^2·K]
h_R: Radiative heat transfer coefficient [W/m^2·K]
H: Humidity of air-water mixture [kg H$_2$O/kg dry air]

$$H = \frac{p_A}{P - p_A} \times \frac{18.02}{28.97}$$

H_P: Percentage humidity

$$H_P = 100\frac{H}{H_S}$$

H_R: Percentage relative humidity

$$H_R = 100\frac{p_A}{p_{AS}}$$

H_S: Saturation humidity [kg H$_2$O/kg dry air]

$$H_S = \frac{p_{AS}}{P - p_{AS}} \times \frac{18.02}{28.97}$$

H_y, H'_G: Total enthalpy of air-water gas [kJ/kg dry air]

$$H_y\left[\text{kJ/kg dry air}\right] = c_S\left(T - T_o\right) + H\lambda_o = \left(1.005 + 1.88H\right)\left(T - T_o\right) + H\lambda_o$$

H'_S: Total enthalpy of wet solid [kJ/kg dry solid]

$$H'_S = c_{ps}\left(T_S - T_o\right) + Xc_{pH_2O}\left(T_S - T_o\right)$$

k: Mass transfer coefficient [kmol/(s·m^2·mol frac)]
k_y: Mass transfer coefficient of water [kmol/(s·m^2·mol frac)]
k_M: Metal tray thermal conductivity [W/m·K]
k_S: Solid thermal conductivity [W/m·K]
L_s: Mass rate of dry solid [kg dry solid/h] (≡ *inert* mass flow rate) **(Continuous dryer)**
L_s: Mass of dry solid [kg] **(Batch dryer)**
M_i: Molecular weight of specie i [kg/kmol]
N_{H2O}: Molar flux of water [kmol of H$_2$O evaporating/(s·m^2)]

p_A: Partial pressure of specie A (water in drying) [mmHg or kPa]

p_{AS}: Equilibrium vapor pressure of specie A (water in drying) [mmHg or kPa]

$$p_{AS}\left[\text{mmHg}\right]=\exp\left(20.386-\frac{5132}{T\left[\text{K}\right]}\right)$$

Q: Heat added or removed [kJ/h]

R: Drying rate [kg H_2O/h·m^2]

$$R=-\frac{L_S}{A}\frac{dX}{dt}$$

R_C: Constant drying rate

t: Drying time [h]

T: Dry bulb temperature (°C/K)

T_0: Reference temperature (°C/K)

T_S: Adiabatic saturation temperature (°C/K) **(Humid air)**

T_S: Surface temperature (°C/K) **(Dryers)**

T_W: Wet bulb temperature (°C/K)

U_k: Overall heat transfer coefficient [W/m^2·K]

$$U_K=\frac{1}{R_{tot}}=\frac{1}{1/h_c+z_M/k_M+z_S/k_S}$$

v_H: Humid volume of air-water mixture [m^3/kg dry air]

$$v_H=(2.83\text{x}10^{-3}+4.56\text{x}10^{-3}H)T\ [\text{K}]$$

v: Gas superficial velocity [m/s]

W: Weight of wet solid [kg]

W_S: Weight of dry solid [kg]

x: Weight fraction of water [kg water / kg solid total] (x for free, x_t for total)

X: Free moisture content [kg water/kg dry solid]

$$X=\frac{x}{1-x}$$

X^*: Equilibrium moisture content [kg water/kg dry solid]

X_C: Critical moisture content [kg water/kg dry solid]

X_t: Total moisture content [kg total water/kg dry solid]

$$X_t=\frac{W-W_S}{W_S}$$

$$X_t=X+X^*$$

y_w: Mole fraction of water vapour in gas at the surface of solid

y: Mole fraction of water in the gas

z_M: Metal tray thickness[m]

z_S: Solid to dry thickness [m]

z: Distance in the dryer bed [m]

Z: Height of a dryer bed [m]

λ: Latent heat of vaporization at T [kJ/kg H_2O]

$$\lambda=H_V-h_l$$

λ_S: Latent heat of vaporization at T_S [kJ/kg H_2O]

$$\lambda_S=2501.4-2.2549T_S-0.002T_S^2$$

λ_W: Latent heat of vaporization at T_W [kJ/kg H_2O]

μ: Viscosity [kg/m·s]

ρ_s: Bulk density of the dry solids [kg/m^3] (includes particle volume, inter-particle void volume)

ρ: Density of the dry solids [kg/m^3]

ρ: Density of the humid air [kg/m^3]

$$\rho=\frac{1+H}{v_H}$$

MODULE 2 - GAS-LIQUID PROCESSES

-Inert: The gas or the liquid that does not transfer from one phase to the other (i.e. the solvent)
-Total: Inert + solute

a: Specific surface of the packing [m^2 /m^3]
A: Absorption factor

$A = L/mV$, $A=1/S$ (Stripping factor)

c_A: Concentration of A [mol/L]
D_{AB}: Diffusion coefficient of A in B [m^2/h]
f_P: Relative mass transfer coefficient
F_P: Packing factor [ft^{-1}]
G_G, G_L: Mass flow rate of gas, liquid [lb$_m$/s·ft^2]
G_x, G_y: Mass flow rate of gas, liquid / cross-section (≡ Mass flux) [kg /s·m^2]
H: Henry’s law constant, based on partial pressure [atm/mol fraction]

$$y_A P = p_A = H x_A$$

H': Henry’s law constant, based on molar fraction

$$y_A = H' x_A$$

H_G: Height of a transfer unit based on the gas film [m]

$$H_G = \frac{V}{k'_y\, aS} = \frac{V}{k_y a\left(1-y\right)_{iM}\, S}$$

H_L: Height of a transfer unit based on the liquid film [m]
H_{OG}: Overall-height of a gas-transfer unit [m]

$$H_{OG} = \frac{V}{K'_y\, aS} = \frac{V}{K_y a\left(1-y\right)_{iM}\, S}$$

$$H_{OG} = H_G + \left(mV/L\right) H_L$$

H_{OL}: Overall-height of a liquid-transfer unit [m]

$$H_{OL} = H_L + \left(L/mV\right) H_G$$

$HEPT$: Height of a theoritical stage [m]

$$HEPT = H_{OG} \frac{\ln(1/A)}{(1-A)/A}$$

k_x: Mass transfer coefficient in liquid [kmol/(s·m^2·mol frac)] **(A diffusing through stagnant non-diffusing B)**

$$k_x = \frac{k'_x}{x_{BM}}$$

k_y: Mass transfer coefficient in gas [kmol/(s·m^2·mol frac)] **(A diffusing through stagnant non-diffusing B)**

$$k_y = \frac{k'_y}{y_{BM}}$$

k'_x:Mmass transfer coefficient in liquid [kmol/(s·m^2·mol frac)] **(Equimolar counter diffusion)**
k'_y: Mass transfer coefficient in gas [kmol/(s·m^2·mol frac)] **((Equimolar counter diffusion)**
K_x: Overall mass transfer coefficient reltive to liquid[kmol/(s·m^2·mol frac)] **(A diffusing through stagnant non-diffusing B)**

$$\frac{1}{K_x} = \frac{1}{m'' k_y} + \frac{1}{k_x} \Leftrightarrow \frac{1}{K'_x \big/ \left(1-x_A\right)_{*M}} = \frac{1}{m'' k'_y \big/ \left(1-y_A\right)_{iM}} + \frac{1}{k'_x \big/ \left(1-x_A\right)_{iM}}$$

K_y: Overall mass transfer coefficient relative to gas [kmol/(s·m^2·mol frac)] **(A diffusing through stagnant non-diffusing B)**

$$\frac{1}{K_y}=\frac{1}{k_y}+\frac{m'}{k_x}\Leftrightarrow\frac{1}{K'_y/(1-y_A)_{*M}}=\frac{1}{k'_y/(1-y_A)_{iM}}+\frac{m'}{k'_x/(1-x_A)_{iM}}$$

K'_x: Overall mass transfer coefficient relative to liquid[kmol/(s·m^2·mol frac)] **(Equimolar counter diffusion)**

K'_y: Overall mass transfer coefficient relative to gas [kmol/(s·m^2·mol frac)] **(Equimolar counter diffusion)**

J^*_{Az}: Diffusive flux of A in z-direction [mol/ h·m^2]

L: Total molar flow rate of liquid (≡ inert molar flux) [kmol/h·m^2]

$$L=\left(\frac{L'}{1-x}\right)$$

L': Inert molar flow rate of liquid (≡ inert molar flux) [kmol/h·m^2]

m: Approximation of the equilibrium line slope (= *H'* when Henry's law is applicable)

*m': S*lope of EM

$$\text{slope of } \overline{EM}=m'=\frac{y_{Ai}-y_A^*}{x_{Ai}-x_{AL}}$$

m'': Slope of MD

$$\text{slope of } \overline{MD}=m''=\frac{y_{AG}-y_{Ai}}{x_A^*-x_{Ai}}$$

M_i: Molecular weight of specie *i* [kg/kmol]

n_A: Molar rate of A [kmol of A/s]

N_A: Molar flux of A [kmol of A/s·m^2]

$N_A=k_y(y_{AG-}y_{Ai})=k_x(x_{Ai-}x_{AL})\Longrightarrow-\frac{k_x}{k_y}=\frac{y_{AG-}y_{Ai}}{x_{Ai-}x_{AL}}$ **(A diffusing through stagnant non-diffusing B)**

$N_A=k'_y(y_{AG-}y_{Ai})=k_{\prime x}(x_{Ai-}x_{AL})\Longrightarrow-\frac{k\prime_x}{k\prime_y}=\frac{y_{AG-}y_{Ai}}{x_{Ai-}x_{AL}}$ **(Equimolar counter diffusion)**

$N_A=K'_y(y_{AG-}y_A^*)=K'_x(x_A^*-x_{AL-})$ (**Equimolar counter diffusion (overall)**)

N: Number of equilibrium stages

N_G*:* Number transfer unit based on the gas film

N_L*:* Number transfer unit based on the liquid film

N_{OG}*:* Number of transfer unit based on overall-height of a gas-transfer unit

N_{OL}*:* Number of transfer unit based on overall-height of a liquid-transfer unit

P: Total pressure [atm]

p_A*:* Partial pressure of solute A [atm]

R: Gas constant [J/mol·K]

S: Cross-sectionnal area of the tower [m^2]

T: Temperature (°C/K)+

v, v_G: Superficial velocity, superficial velocity of gas [m/s] ([ft/s])

V: Total molar flow rate of gas (≡ inert molar flux) [kmol/h·m^2] (≡ inert molar flux)

$$V=\left(\frac{V'}{1-y}\right)$$

V': Inert molar flow rate of gas (≡ inert molar flux) [kmol/h·m^2]

V_A*:* Solute molar volume [m^3/kmol] **(for diffusivity calculation - liquid)**

x: Molar fraction in liquid phase [mol specie/mol total]

x_A*:* Molar fraction of solute in liquid phase [mol solute/mol total]

x_{Ai}*:* Interface (equilibrium) molar fraction of solute in liquid phase [mol solute/mol total]

x_{AG}*:* Bulk molar fraction of solute in liquid phase [mol solute/mol total]

x^*_A: Molar fraction of solute in liquid phase in equilibrium with y_{AG}[mol solute/mol total]

$$(1-x_A)_{*M} = \frac{(1-x_{AL})-(1-x_A^*)}{\ln\left[(1-x_{AL})/(1-x_A^*)\right]}$$

$x_{BM} \equiv (x_B)_{iM}$: Log mean mole fraction of inert or stagnant B (= $(1\text{-}x_A)_{iM}$)

$$(1-x_A)_{iM} = \frac{(1-x_{AL})-(1-x_{Ai})}{\ln\left[(1-x_{AL})/(1-x_{Ai})\right]} = \frac{(x_{BL})-(x_{Bi})}{\ln\left[(x_{BL})/(x_{Bi})\right]} = (x_B)_{iM}$$

X: Liquid molar fraction parameter for straight operating line

$$X = \frac{x}{1-x}$$

y: Molar fraction in gas phase [mol specie /mol total]

y_A: Molar fraction of solute in gas phase [mol solute/mol total]

y_{Ai}: Interface (equilibrium) molar fraction of solute in gas phase [mol solute/mol total]

y_{AG}: Bulk molar fraction of solute in gas phase [mol solute/mol total]

y^*_A: Molar fraction of solute in gas phase in equilibrium with x_{AL}[mol solute/mol total]

$$(1-y_A)_{*M} = \frac{(1-y_A^*)-(1-y_{AG})}{\ln\left[(1-y_A^*)/(1-y_{AG})\right]}$$

$y_{BM} \equiv (y_B)_{iM}$: Log mean mole fraction of inert or stagnant B (= $(1\text{-}y_A)i_M$)

$$(1-y_A)_{iM} = \frac{(1-y_{Ai})-(1-y_{AG})}{\ln\left[(1-y_{Ai})/(1-y_{AG})\right]} = \frac{(y_{Bi})-(y_{BG})}{\ln\left[(y_{Bi})/(y_{BG})\right]} = (y_B)_{iM}$$

Y: Gas molar fraction parameter for straight operating line

$$Y = \frac{y}{1-y}$$

z: Distance [m]

Z: Height of packed tower [m]

$Z=N(HEPT)$ or $Z=N_{OG}H_{OG}= N_{OL}H_{OL}= N_GH_G= N_LH_L$

μ: Viscosity [kg/m·s] [Pa·s]

φ: Association parameter **(for diffusivity calculation - liquid)**

ν: Kinematic viscosity [centistokes]

$\sum \nu_i$: Sum of structural volume increments **(for diffusivity calculation - gas)**

ρ_G, ρ_L : Density of gas, liquid [$\text{lb}_\text{m}/\text{ft}^3$]

MODULE 3 - VAPOUR-LIQUID PROCESSES

A - subscript: Distillate product (more volatile)
B - subscript: Bottoms product (less volatile)
D: Distillate stream total flow rate [kmol/h]
E_O: Overall tray efficiency
E_M: Murphree tray efficiency
F: Feed stream total flow rate [kmol/h]
H_F:Specific enthalpy of feed [kJ/kmol]
H_L: Specific enthalpy of liquid [kJ/kmol]
H_V: Specific enthalpy of vapour [kJ/kmol]
L: Liquid stream total flow rate [kmol/h]
m-subscript: Stripping section
M: Mixing point [x_A, y_A coordinates]
n-subscript: Enriching section
N: Number of stages
N_m: Minimum number of stages
p_A: Partial pressure of solute A [Pa] (Often P_A in other books)
P_A: Equilibrium vapour pressure of pure solute A [Pa] (Often P_A* or P_A° in other books)
P: Total pressure [Pa]
P: Operating point [x_A, y_A coordinates]
q: Fraction of liquid in the feed stream

$$q = \frac{\left(L_m - L_n\right)}{F}$$

Q: Heat added or removed [kJ/h]
Q_D: Condenser duty [kJ/h]
Q_R: Reboiler duty [kJ/h]
R: Reflux ratio

$$R = \frac{L_n}{D}$$

R_m: Minimum reflux ratio
S: Injected steam total flow rate [kmol/h]
T_b: Boiling point [°C]
V: Vapour stream total flow rate [kmol/h]
W: Bottoms stream total flow rate [kmol/h]
x_A: Molar fraction of solute A in liquid phase [mol solute/mol total]
x: Molar fraction of solute A in liquid stream [mol solute/mol total]
x_F: Molar fraction of solute A in feed stream [mol solute/mol total]
x_D: Molar fraction of solute A in distillate stream [mol solute/mol total]
x_B: Molar fraction of solute A in bottoms stream [mol solute/mol total]
y_A: Molar fraction of solute A in vapour phase [mol solute/mol total]
y: Molar fraction of solute A in vapour stream [mol solute/mol total]
α: Relative volatility (also refered to as the separation factor

$$\alpha_{AB} = \frac{y_A/x_A}{y_B/x_B} = \frac{y_A/x_A}{\left(1-y_A\right)/\left(1-x_A\right)}$$

μ_L: Molar average viscosity in [cP]

MODULE 4 - LIQUID-LIQUID EXTRACTION

A - subscript: Solute A
A: Extraction factor for Kremser equation (immiscible liquids)

$$A = \frac{L}{mV}$$

B - subscript: Component B - Liquid to be raffinated (feed) → Raffinate
C - subscript: Solvent C → Extract
E : Extract mass [kg] or to designate it
m: Slope of the equilibrium line (immiscible liquids)
M : Mixing point mass (=E+R) [kg] or to designate it
L: Feed stream total flow rate [kg/h] (generally contains A and B at the inlet) → Raffinate
L_0: Feed stream total flow rate [kg/h] (at the inlet)
L_N: Raffinate stream total flow rate [kg/h] (at the outlet)
L': Feed stream flow rate [kg/h] – only B (for immiscible liquids)
N: Number of stages
V: Solvent stream total flow rate [kg/h] (generally contains C at the inlet) → Extract
V_1: Extract stream total flow rate [kg/h] (at the outlet)
V_{N+1}: Solvent stream total flow rate [kg/h] (at the outlet)
V_{min}: Minimum solvent stream total flow rate [kg/h]
V': Solvent stream flow rate [kg/h] – only C
R : Raffinate mass [kg] or to designate it
P: Plait point
x_A: Mass fraction of solute A in raffinate stream [kg solute/kg total]
x_B: Mass fraction of solvent B in raffinate stream [kg B/kg total]
x_C: Mass fraction of component C in raffinate stream [kg C/kg total]
x_E: Mass fraction of solute A in extract [kg solute/kg total]
x_M: Mass fraction of solute A at mixing point [kg solute/kg total] (can be x_{AM})
x_N: Mass fraction of solute A in raffinate stream [kg solute/kg total] (at the outlet - can be x_{AN})
x_R: Mass fraction of solute A in raffinate [kg solute/kg total]
y_A: Mass fraction of solute A in extract stream [kg solute/kg total]
y_B: Mass fraction of solvent B in extract stream [kg B/kg total]
y_C: Mass fraction of component C in extract stream [kg C/kg total]
β : Selectivity

$$\beta = \frac{(wt\% \;\; A\ in\ E)/(wt\% \;\; B\ in\ E)}{(wt\% \;\; A\ in\ R)/(wt\% \;\; B\ in\ R)} = \frac{y_{A1}/y_{B1}}{x_{A1}/x_{B1}}$$

Δ : Operating point

$$\Delta = L_o - V_1 = L_n - V_{n+1} = L_N - V_{N+1}$$

MODULE 5a - LEACHING

A - *subscript:* Solute A
B - *subscript:* Solid B
C - *subscript:* Solvent C
A: Mass of solute A [kg]
B: Mass of solid B [kg]

$$B = N_o L_o = N_N L_N = N_M M$$

C: Mass of solvent C [kg]
L: Slurry flow rate (A+C in underflow)
M : Total mixure flow rate (= *A*+*C* in underflow and overflow) [kg] or to designate it
N: Concentration of solid B in overflow (should be 0) and in underflow

$$N = \frac{\text{kg B}}{\text{kg A + kg C}}$$

V: Solvent flow rate (A+C in overflow)
x_A: Concentrationof solute A in overflow

$$x_A = \frac{\text{kg A}}{\text{kg A + kg C}}$$

x_M: Concentrationof solute A at mixing point
y_A: Concentrationof solute A in underflow

$$y_A = \frac{\text{kg A}}{\text{kg A + kg C}}$$

Δ : Operating point

$$\Delta = L_o - V_1 = L_n - V_{n+1} = L_N - V_{N+1}$$

MODULE 5b - ADSORPTION

b: Adsorption equilibrium constant
c: Concentration of the adsorbate [kg adsorbate/m^3 solution] (equilibrium)
c_b: Concentration of the adsorbate at break point [kg adsorbate/m^3 solution]
c_F: Initial/feed concentration of the adsorbate [kg adsorbate/m^3 solution] (Batch process)
c_0: *F*eed concentration of the adsorbate [kg adsorbate/m^3 solution] (Fixed-bed process)
H : Isotherm affinity constant (gas phase)
H_B : Length utilized up to the break point [m]

$$H_B = \frac{t_u}{t_t} H_{Total}$$

H_T : Total length of bed [m]
H_{UNB} : Length of unused bed [m]

$$H_{UNB} = \left(1 - \frac{t_u}{t_t}\right) H_{total}$$

K : Isotherm affinity constant (liquid phase)
M : Molecular weight of solute (adsorbate) [kg/kmol]
M : Amount of adsorbate [kg]
n : Isotherm parameter
N_o : Avogadro's number (6.023x10^{26}/kmol)
p: Partial pressure of the adsorbate [Pa]
q : Capacity ≡ amount of adsorbate on the adsorbent [kg adsorbate/kg adsorbent] (equilibrium)
q_0 : Mono-layer capacity [kg adsorbate/kg adsorbent]
q_F : Initial amount of adsorbate on the adsorbent [kg adsorbate/kg adsorbent] (Batch process)
S: Volume of solution [m^3]
S_g: Surface of the adsorbent [m^2]
t_b: Break point time [h]
t_t: Time equivalent to the total capacity [h]

$$t_t = \int_0^\infty (1 - \frac{c}{c_o})\ dt$$

t_u: Time equivalent to the usable capacity [h]

$$t_u = \int_0^{t_b} (1 - \frac{c}{c_o})\ dt$$

V : Volume of solute adsorbed [m^3]
V_A: Avogadro's volume (22,400 m^3/kmol)
V_m : Total volume of solute adsorbed in monolayer [m^3]
α : *P*rojected surface area of single molecule [m^2]
θ : Fractional coverage of the surface
ρ : Density (adsorbate, feed, etc.) [kg/m^3, kmol/m^3]