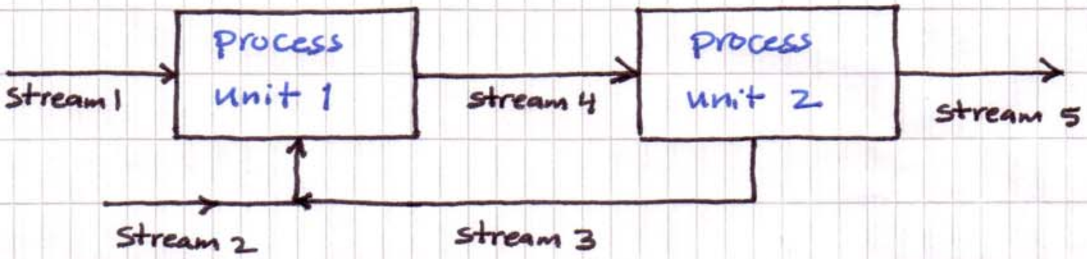
*Chapter 3 : process and process variables :

- Process : an operation or a series of operations that causes a physical/chemical / biological changes, thereby, converting raw material into products.

- Process flowchart (flow sheet) :

Ex :



- Process streams : inputs and outputs of a process units

- Process variables : variables to characterize streams entering and leaving process units.

  Ex : Temperature, pressure, mass (mole) flow rates Volumetric flow rates, Concentrations, ... etc.

- Note that some process variables given and others will be calculated.

** Composition or Concentration :

It has the following forms :

- Density : ratio of mass to volume

$$\rho = \frac{M}{V}$$ It is also called: mass Concentration

ρ is a material physical property

$\rho = \rho(T, p)$: - solids and liquids :

→ slight variation with temperature ; T.

→ almost no variation with pressure ; p.

- Gases :

strong variation with p

Most pure Compounds: as T ↑ ρ ↓ (volume expansion)

as p ↑ ρ ↑ (Volume Compression)

Remember water - an "anomaly" :

as T ↑ ρ ↑ for water in the range (0 - 4 °C)

- Perry's Chemical Engineers Handbook is one of the best handbooks to get physical properties of many pure compounds, solutions, and mixtures.

- Get Comfortable in making (safe) assumptions to simplify things ! .

→ For now we will assume :

- solids and liquids are incompressible : $\rho \neq \rho(p)$

  $\rho = \rho(T)$

- Gases and vapors are Compressible : $\rho = \rho(T, p)$

- **Specific volume** : volume occupied by a unit mass of substance

$$v = \frac{V}{M} = \frac{1}{\rho}$$

→ molar volume $= \dfrac{V}{n}$

→ Molar Concentration or (Concentration) $= \dfrac{n}{V} = \dfrac{1}{\text{Molar volume}}$

- **Specific gravity ; SG** : ratio of the density of a substance to a reference substance at specific conditions :

$$SG = \frac{\rho(T, p)}{\rho_{ref}(T_{ref}, P_{ref})}$$

→ SG is dimensionless

→ For solids and liquids, the most common reference is water at 4°C and 1 atm :

$$\rho_w(1\,atm, 4°C) = 1\ g/cm^3 = 1000\ kg/m^3$$
$$= 62.43\ lbm/ft^3 = 1.941\ slug/ft^3$$

→ see table B.1 in the appendix of your textbook to lookup SG for some liquids and solids at 1 atm.

→ Typically SG is expressed as:

Ex: $SG = 0.6^{20^\circ}_{4^\circ}$: it means that this value of SG for the substance at 20°C with ref. to water at 4°C.

Ex: what is the mass of 395 gal of acetone at 40°C?

$$M = \rho \mathcal{V} = \rho_{water} \, SG \, \mathcal{V}$$

pick up SG for acetone from table B.1:

for acetone: $SG^{20^\circ}_{4^\circ} = ?$ take it by yourself from the table

$M = 2610 \ lb_m$ (pay attention to units)

This is overestimate value of mass why?

because we use SG at 20°C which is larger than SG at the given temperature and thus the mass will be larger (overestimate).

- Specific weight; γ : ratio of the weight of substance to its volume

$$\gamma = \frac{W}{\mathcal{V}} = \frac{mg}{\mathcal{V}} = \rho g \;[=]\; \frac{N}{m^3}$$

$$\frac{lb_f}{ft^3}$$

$$\frac{dyne}{cm^3}$$

_ Chemical Composition of mixture :

Remember that :

1 g-mol of Compound = the sum of the atomic mass of all atoms that Constitute a molecule of the Compound; expressed in (g).

1 kg-mol 〃 〃 = 〃 〃 〃 〃 〃 〃 〃
〃 〃 〃 〃 〃 〃 〃 〃
〃 〃 〃 〃 ; 〃 〃 (kg).

1 lb_m-mol 〃 〃 = 〃 〃 〃 〃 〃 〃 〃
〃 〃 〃 〃 〃 〃 〃 〃
〃 〃 〃 〃 ; 〃 〃 (lb_m)

$$\Rightarrow \frac{\text{the sum of the atomic mass of atoms of molecule}}{1 \text{ gmol}} = 1 = \text{Mwt of Component}$$

Mwt : Molecular Mass (weight: Common mistake)

Thus, it can be said that Molecular mass is a Conversion factor between mass and moles

→ Also, remember that :

1 g-mole of Compound = 6.02×10^{23} (Avogadro's number) molecules of that compound

→ we it is mentioned (mol) it means g-mol .

EX: How many of each of the following are contained within 100 g of CO_2 (Mwt = 44.01 g/gmol):

(a) moles CO_2 : $\dfrac{100\,g\,CO_2 \;\big|\; 1\text{ g-mol }CO_2}{\;\big|\; 44.01\,g\,CO_2} = 2.272\text{ gmol }CO_2$

(b) lb_m-mol CO_2: $\dfrac{100\,g\,CO_2 \;\big|\; 1\,lb_m \;\big|\; 1\,lb_m\text{-mol }CO_2}{\;\big|\; 453.6\,g \;\big|\; 44.01\,lb_m\,CO_2}$

$= 5.009 \times 10^{-3}\ lb_m\text{-mol }CO_2$

(c) gmoles of C : $\dfrac{2.272\text{ gmol }CO_2 \;\big|\; 1\text{ mol C}}{\;\big|\; 1\text{ mol }CO_2}$

$= 2.272$ gmol

(d) gmoles of O : $\dfrac{2.272\text{ gmol }CO_2 \;\big|\; 2\text{ gmol O}}{\;\big|\; 1\text{ mol }CO_2} = 4.544$ gmol

(e) grams of O_2 : $\dfrac{2.272\text{ gmol }CO_2 \;\big|\; 1\text{ mol }O_2 \;\big|\; 32\,g\,O_2}{\;\big|\; 1\text{ mol }CO_2 \;\big|\; 1\text{ gmol }O_2}$

$= 73\ g\ O_2$

(f) molecules of CO_2 : $\dfrac{2.272\text{ gmol }CO_2 \;\big|\; 6.023 \times 10^{23}\text{ molecules}}{\;\big|\; 1\text{ gmol }CO_2}$

$= 1.368 \times 10^{24}$ molecules CO_2

→ Chemical Compositions:

▲ Mass fraction : $X_A = \dfrac{\text{mass of species A}}{\text{total mass of mixture}}$

Ex : X_A = 50 wt% or 50% w/w or 50% by mass
all these notations indicate mass fraction.

▲ Mole fraction : $y_A = \dfrac{\text{moles of A}}{\text{total moles}}$

Ex: y_A = 30 mol% or 30% mol/mol or 30% by mol.

▲ Volume fraction : $V_A = \dfrac{\text{Volume of A}}{\text{total Volume}}$

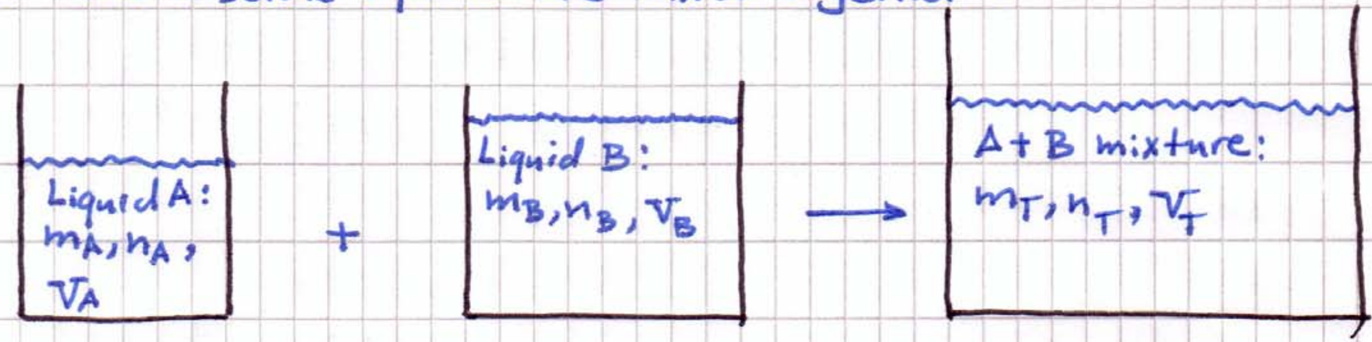
Ex: V_A = 54 Vol% or 54% Vol/Vol or 54% by Volume
or V/V

* Generalizations:

- Solids and liquids generally go by mass or mole fractions
- Gases and vapors generally go by mole or volume fractions

* Non-additivity of liquid volumes :

→ If two miscible liquids are mixed together :



For miscible liquids :- Volumes of liquids are not additive,

$$V_T \neq V_A + V_B$$

although it is usually closed to the additivity.

But :

$m_T = m_A + m_B$ "law of Conservation of mass"

$n_T = n_A + n_B$ "just mixing and no reaction between A and B"

* For mixtures : $\sum_{i=1}^{N} x_i = 1$ (verify that) ?!

$\sum_{i=1}^{N} y_i = 1$ (verify that) ?!

* If you do NOT have density data for liquid mixture; assume Volume additivity of the Components:

$$V_T = V_A + V_B + V_C + \cdots \quad \text{(safe assumption)}$$

But from density definition $\rho = \frac{M}{V} \Rightarrow V = \frac{M}{\rho}$

$$\Rightarrow \frac{M_T}{\rho} = \frac{M_A}{\rho_A} + \frac{M_B}{\rho_B} + \frac{M_C}{\rho_C}$$

Divide by M_T (total mass of mixture):

$$\frac{1}{\rho} = \frac{x_A}{\rho_A} + \frac{x_B}{\rho_B} + \frac{x_C}{\rho_c} + \cdots$$

and in general for a liquid mixture of N species:

$$\boxed{\frac{1}{\rho} = \sum_{i=1}^{N} \frac{x_i}{\rho_i}}$$

ρ : Density of the mixture

* How can we calculate the average molecular weight of a mixture?

The molecular weight of any species i :

$$Mwt_i = \frac{M_i}{n_i}$$

and the Average molecular weight of the mixture is

$$\overline{Mwt} = \frac{M_T}{n_T} = \frac{\text{total mass}}{\text{total moles}}$$

$$M_T = M_1 + M_2 + M_3 + \cdots + M_N$$

$$\overline{Mwt}\, n_T = Mwt_1 n_1 + Mwt_2 n_2 + Mwt_3 n_3 + \cdots + Mwt_N n_N$$

Divide by n_T :

$$\overline{Mwt} = Mwt_1\, y_1 + Mwt_2\, y_2 + Mwt_3\, y_3 + \cdots + Mwt_N\, y_N$$

$$\therefore \boxed{\overline{Mwt} = \sum_{i=1}^{N} y_i\, Mwt_i .}$$

and in terms of mass fractions ; x_i :

$$n_T = n_1 + n_2 + n_3 + \cdots + n_N$$

But $n = \dfrac{M}{Mwt}$

$$\Rightarrow \frac{M_T}{\overline{Mwt}} = \frac{M_1}{Mwt_1} + \frac{M_2}{Mwt_2} + \frac{M_3}{Mwt_3} + \cdots + \frac{M_N}{Mwt_N}$$

Divide by M_T :

$$\frac{1}{\overline{Mwt}} = \frac{x_1}{Mwt_1} + \frac{x_2}{Mwt_2} + \frac{x_3}{Mwt_3} + \cdots + \frac{x_N}{Mwt_N}$$

$$\therefore \boxed{\frac{1}{\overline{Mwt}} = \sum_{i=1}^{N} \frac{x_i}{Mwt_i}}$$

* Remember that : $\boxed{C = \rho / Mwt}$

Ex : Calculate the average molecular weight of air based on the following provided information :

(a) Its approximated molar Composition: 79% N_2 and 21% O_2

$$\overline{Mwt} = \sum y_i \, Mwt_i = y_{N_2} Mwt_{N_2} + y_{O_2} Mwt_{O_2}$$
$$= (0.79)(28) + (0.21)(32)$$
$$= 28.8 \frac{g}{gmol} \cong 29 \frac{g}{gmol}$$

(b) Its approximated mass Composition of 76.7% N_2 and 23.3% O_2

$$\frac{1}{\overline{Mwt}} = \sum \frac{x_i}{Mwt_i} = \frac{x_{N_2}}{Mwt_{N_2}} + \frac{x_{O_2}}{Mwt_{O_2}}$$
$$= \frac{0.767}{28} + \frac{0.233}{32}$$
$$\Rightarrow \overline{Mwt} = 28.8 \cong 29 \ g/gmol$$

Ex : A mixture of gases has the following mass Composition :

O_2 : 16% ; CO : 4.0% ; CO_2 : 17% ; N_2 = ?

(a) what is the mass Composition of N_2 :

$$\sum x_i = 1 \Rightarrow 0.16 + 0.04 + 0.17 + x_{N_2} = 1$$

$$\Rightarrow x_{N_2} = 0.63$$

(b) what is the molar Composition of this mixture:

Choose a basis of Calculation !

Basis : 100 g of gas mixture. Then the gas has :

$M_{O_2} = 16 g$ $\quad$ $M_{CO_2} = 17 g$

$M_{CO} = 4 g$ $\quad$ $M_{N_2} = 63 g$

Now wee need molecular weight information in order to determine the number of moles of individual species:

$$n_{O_2} = \frac{16 g \,|\, 1 mol}{\,|\, 32 g} = 0.5 \text{ gmol}$$

$$n_{CO} = \frac{4 g \,|\, 1 gmol}{\,|\, 28 g} = 0.143 \text{ gmol}$$

$$n_{CO_2} = \frac{17 g \,|\, 1 gmol}{\,|\, 44 g} = 0.386 \text{ gmol}$$

$$n_{N_2} = \frac{63 g \,|\, 1 gmol}{\,|\, 28 g} = 2.25 \text{ gmol}$$

$$n_T = 3.279 \text{ gmol}$$

$$\Rightarrow y_{O_2} = \frac{0.5}{3.279} = \frac{n_{O_2}}{n_T} = 0.152$$

$$y_{CO} = \frac{0.143}{3.279} = 0.044 \quad ; \quad y_{N_2} = \frac{2.25}{3.279} = 0.686$$

$$y_{CO_2} = \frac{0.386}{3.279} = 0.118$$

Check using: $\sum y_i = 1$ ✓

→ Thus, to Convert molar Composition of some mixture to mass Composition, you must take a molar basis as 100 mol of mixture.

→ and to Convert mass composition of mixture to molar Composition, you must take a mass basis as 100 Kg of mixture for example.

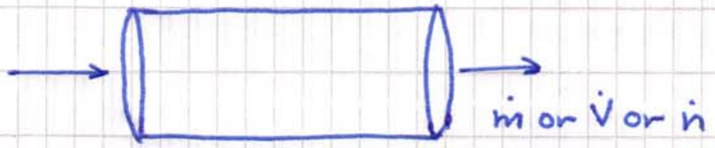
** Flowrates : the rate at which material being trasported through the process stream.

* Forms of flowrates :

- mass flow rate ; $\dot{m} = \frac{\text{mass}}{\text{time}}$ [=] kg/s
  slug/s
  lb_m/s

- Volumetric flow rate ; $\dot{V}$ or $Q = \frac{\text{Volume}}{\text{time}}$ [=] $\frac{m3}{s}$
  [=] $\frac{ft^3}{s}$

- Molar flow rate ; $\dot{n} = \frac{\text{moles}}{\text{time}}$



$$\text{Density} ; \rho = \frac{m}{V} = \frac{\dot{m}}{\dot{V}} \Rightarrow \dot{m} = \rho \dot{V}$$
$$\text{or } \dot{m} = \rho Q$$

$$\text{Molar Concentration} ; C = \frac{n}{V} = \frac{\dot{n}}{\dot{V}} \Rightarrow \dot{n} = C \dot{V}$$
$$\text{or } \dot{n} = C Q$$

$$x_i = \frac{m_i}{m_{total}} = \frac{\dot{m}_i}{\dot{m}_{total}} \; ; \; y_i = \frac{n_i}{n_{total}} = \frac{\dot{n}_i}{\dot{n}_{total}}$$

Ex : A solution Contains 15% A by mass and 20% B by mole. Calculate:

(a) Mass of A in 175 Kg Solution :

$$x_A = 0.15 = \frac{m_A}{m_t} \Rightarrow m_A = (0.15)(m_t) = (0.15)(175)$$
$$= 26 \text{ Kg A}$$

(b) The mass flow rate of A in a stream of solution flowing at 53 lbm / hr :

$$x_A = \frac{\dot{m}_A}{\dot{m}_t} \Rightarrow \dot{m}_A = x_A \, \dot{m}_t = (0.15)(53) = 7.95 \frac{\text{lb}_m \text{ A}}{\text{hr}}$$

(c) The molar flow rate of B in a stream flowing at 1000 $\frac{\text{mol}}{\text{min}}$

$$y_B = \frac{\dot{n}_B}{\dot{n}_t} \Rightarrow \dot{n}_B = y_B \, \dot{n}_t = (0.2)(1000) = 200 \frac{\text{mol B}}{\text{min}}$$

Ex : A 0.5 molar aqueous solution of sulfuric acid flows into a process unit at rate of 1.25 $\frac{m^3}{min}$. The specific gravity of solution is 1.03^{20}_{4}. Calculate

$C_{H_2SO_4} = 0.5 \text{ M} = 0.5 \frac{\text{M}}{\text{L}}$; $Q = \dot{V} = 1.25 \frac{m^3}{min}$, $SG = 1.03^{20}_{4}$

(a) The mass concentration of H_2SO_4 in kg/m³ :

$$\rho_{H_2SO_4} = C_{H_2SO_4} * \overline{Mwt}_{H_2SO_4} =$$

$$= \frac{0.5 \text{ mol}}{\text{L}} \left| \frac{98 \text{ g}}{\text{mol}} \right| \frac{1 \text{ kg}}{1000 \text{ g}} \left| \frac{1000 \text{ L}}{1 \text{ m}^3} \right. = 49 \frac{\text{kg}}{\text{m}^3}$$

(b) The mass flow rate of solution in kg/s :

$\dot{m} = \rho Q$ But $\rho = SG \rho_w$

assume that $\rho_w = 1 \frac{g}{cm^3}$

$\Rightarrow \rho = (1.03)(1) = 1.03 \frac{g}{cm^3}$

$$\dot{m} = \frac{1.03\,g}{cm^3} \cdot \frac{1.25\,m^3}{min} \cdot \frac{1\,kg}{1000\,g} \cdot \frac{(100\,cm)^2}{1\,m^3} \cdot \frac{1\,min}{60\,s}$$

$= 21.5\ kg/s$

(c) The mass flow rate of H_2SO_4 in kg/s :

$$\rho_{H_2SO_4} = \frac{\dot{m}_{H_2SO_4}}{\dot{V}} \Rightarrow \dot{m}_{H_2SO_4} = (\rho_{H_2SO_4})\, \dot{V}$$

$$\Rightarrow \dot{m}_{H_2SO_4} = \frac{49\,kg}{m^3} \cdot \frac{1.25\,m^3}{min} \cdot \frac{1\,min}{60\,s} = 1.02\,\frac{kg}{s}$$

(d) The mass fraction of H_2SO_4 :

$$x_{H_2SO_4} = \frac{\dot{m}_{H_2SO_4}}{\dot{m}} = \frac{1.02}{21.5} = 0.05\ \frac{kg\ H_2SO_4}{kg\ solution}$$

** Remark: The concentrations of trace species in mixtures are expressed in terms of :

- parts per million (ppm_i) = $y_i \times 10^6$ for gas or $x_i \times 10^6$ for liquids
- Parts per billion (ppb_i) = $y_i \times 10^9$ for gas or $x_i \times 10^9$ for liquids

** Temperature; T :

- Temperature measures kinetic energy of molecules (internal energy of substances).

- The temperature of the body is a measure of its thermal state in reference to its power to transfer heat to other bodies.

* Devices for measuring temperature : Thermometer
  Thermocouple

* Temperature scales : Celsius; °C " SI units "
  Fahrenheit, °F " British units "

These two scales are defined using the freezing point; T_f; and boiling point; T_b; of water at 1 atm.

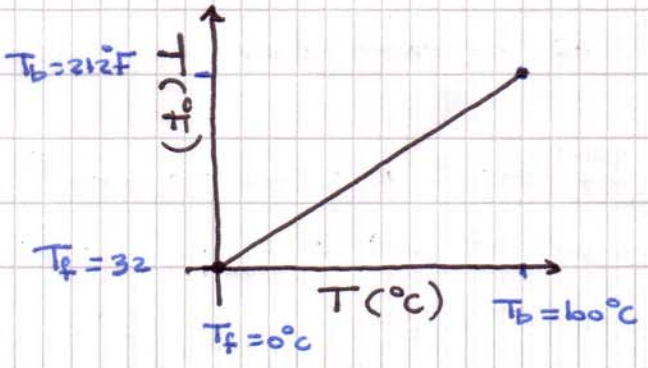
Thus the relationship between these two scales is linear.

<u>Celsius scale</u> : $T_f = 0\,°C$ $\quad T_b = 100\,°C$

<u>Fahrenheit scale</u> : $T_f = 32\,°F$ $\quad T_b = 212\,°F$

$$T(°F) = a\,T(°C) + b$$

$$a = \text{slope} = \frac{212-32}{100-0} = 1.8$$



$$T(°F) = 1.8\,T(°C) + b$$

$$32 = (1.8)(0) + b \Rightarrow b = 32$$

$\Rightarrow$ The relationship between °C and °F scales is:

$$\boxed{T(°F) = 1.8\,T(°C) + 32}$$

* The lowest temperature at which all molecular motion stops is $-273.15\ °C = -459.67\ °F$

* This leads to the definition of <u>absolute temperature scales:</u>

<u>SI units</u>: Kelvin; K Scale: $\boxed{T(K) = T(°C) + 273.15}$

<u>British units</u>: Rankine, °R scale: $\boxed{T(°R) = T(°F) + 459.67}$

Also you can derive the relationship between °R and °K scales:

$$\boxed{T(°R) = 1.8\,T(K)}$$

→ Remember that the absolute temperature can not have negative values neither in K nor in °R

Ex: $T = -20\ °C$ ✓ $\qquad T = \cancel{-300}\ °C < -273.15°C$

$T = \cancel{-5}\ K$ (absolute T) $\qquad T = -300°F$ ✓

$T = \cancel{-3}\ °R$ (absolute) $\qquad T = \cancel{-500}\ °F < -459.67°F$

* standard condition for temperature : 0 °C

* Conversion factors for temperature difference ; ΔT :

$$\Delta T = T_{final} - T_{initial} = T_f - T_i$$

- let us return back to unit Conversion Subject :

Ex: If you have time in seconds $t(s)$ and you would like to convert it to time in minute ; $t(min)$. what will you do?

$$t(min) = \frac{t(s)}{60}$$

. This is eq. and we must have unit consistency in it. Thus; it must be written as :

$$t(min) = \frac{t(s)}{\boxed{60}} \left| \boxed{\frac{min}{s}} \right.$$

⇒ The Conversion factor beetwen (min) an (s) is 1 min = 60 s as we Know.

Let us apply this on ΔT eq. :

$$\Delta T = T_f - T_i$$

$$T_f(°F) = 1.8\, T_f(°C) + 32 \quad \text{----} \; ①$$

$$T_i(°F) = 1.8\, T_i(°C) + 32 \quad \text{---} \; ②$$

subtract eq. (2) from eq. (1):

$$T_f(^\circ F) - T_i(^\circ F) = 1.8\left[T_f(^\circ C) - T_i(^\circ C)\right]$$

$$\therefore \; \Delta T(^\circ F) = 1.8 \; \Delta T(^\circ C)$$

Now to have unit consistency in both sides:

$$\Delta T(^\circ F) = 1.8\,\Delta T(^\circ C)\left|\frac{^\circ F}{^\circ C}\right.$$

∴ for ΔT the conversion between °F and °C is

$$\boxed{1.8\,^\circ F = 1\,^\circ C}$$

You can do the same analysis to find conversion between different T units for ΔT:

$$\Delta T(K) = \Delta T(^\circ C)\left|\frac{K}{^\circ C}\right. \Rightarrow \boxed{1\ K = 1\ ^\circ C}$$

$$\Delta T(^\circ R) = \Delta T(^\circ F)\left|\frac{^\circ R}{^\circ F}\right. \Rightarrow 1\,^\circ R = 1\,^\circ F$$

$$\Delta T(^\circ R) = 1.8\,\Delta T(^\circ K)\left|\frac{^\circ R}{^\circ K}\right. \quad \boxed{1.8\,^\circ R = 1\ K}$$

Ex : Consider an initial temperature; $T_i = 20°F$ and final temperature, $T_f = 80°F$:

(a) Calculate T_i and T_f in °C :

$$T_i(°C) = \frac{T_i(°F) - 32}{1.8} = \frac{20-32}{1.8} = \frac{-12}{1.8}$$

$$= -6.67°C$$

$$T_f(°C) = \frac{T_f(°F) - 32}{1.8} = \frac{80-32}{1.8} = \frac{48}{1.8}$$

$$= 26.67°C$$

(b) Find temperature difference ΔT in °C using:

(1) The results of part (a) :

$$\Delta T(°C) = T_f(°C) - T_i(°C) = 26.67 - -6.67$$

$$= 33.3°C$$

(b) ΔT Conversion factors :

$$\Delta T(°F) = T_f(°F) - T_i(°F) = 80 - 20 = 60°F$$

$$\Delta T = \frac{60°F \;\Big|\; 1°C}{\;\;\Big|\; 1.8°F} = 33.3°C$$ The same answer as in (1).

* Remark: when you would like to Convert quantities in which temperature unit is involved; you must know the basic definition of this quantity to see if temperature unit is related to T or ΔT

Ex: Convert heat capacity of $4\ \frac{J}{g\cdot°C}$ to its equivalent in $\frac{J}{g\cdot°F}$?

So you must know the definition of heat capacity, C_p, in terms of temperature to see if it is T or ΔT in that definition; we know that:

$Q = m C_p \Delta T$ Q: heat

$$\Rightarrow C_p = \frac{Q}{m\,\Delta T} \quad [=] \quad \frac{J}{g\cdot°C}$$

so it is ΔT thus

$$C_p = \frac{4\ J}{g\cdot°C}\left|\frac{1\ °C}{1.8\ °F}\right. = 2.22\ \frac{J}{g\cdot°F}$$

Ex: The heat Capacity of Ammonia as a function of temp. is given by:

$$C_p\left(\frac{Btu}{lb_m\cdot°F}\right) = 0.487 + 2.29\times10^{-4}\,T(°F)$$

(a) Find the heat capacity at T = 80°F in $\frac{J}{g\cdot°C}$

$$C_p\left(\frac{\text{Btu}}{\text{lb}_m\cdot{}^\circ\text{F}}\right) = 0.487 + (2.29\times10^{-4})(80) = 0.505\ \frac{\text{Btu}}{\text{lb}_m\cdot{}^\circ\text{F}}$$

$$= \frac{0.505\ \text{Btu}}{\text{lb}_m\ {}^\circ\text{F}} \left| \frac{1\ \text{J}}{9.486\times10^{-4}\ \text{Btu}} \right| \frac{1\ \text{lbm}}{453.593\ \text{g}} \left| \frac{1.8\ {}^\circ\text{F}}{1\ {}^\circ\text{C}} \right. = 2.11\ \frac{\text{J}}{\text{g}\ {}^\circ\text{C}}$$

(b) Determine an expression to have C_p in $\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}$ in terms of

T in °C :

$$T({}^\circ\text{F}) = 1.8\,T({}^\circ\text{C}) + 32$$

$$C_p\left(\frac{\text{Btu}}{\text{lb}_m\cdot{}^\circ\text{F}}\right) = C_p\left(\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}\right) \left| \frac{9.486\times10^{-4}\ \text{Btu}}{1\ \text{J}} \right| \frac{453.593\ \text{g}}{1\ \text{lbm}} \left| \frac{1\ {}^\circ\text{C}}{1.8\ {}^\circ\text{F}} \right.$$

$$= 0.239\, C_p\left(\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}\right)$$

Substitute for $T({}^\circ\text{F})$ and $C_p\left(\frac{\text{Btu}}{\text{lbm}\cdot{}^\circ\text{F}}\right)$ in the given expression:

$$0.239\, C_p\left(\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}\right) = 0.487 + 2.29\times10^{-4}\left[1.8\,T({}^\circ\text{C}) + 32\right]$$

$$\therefore C_p\left(\frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}\right) = 2.068 + 1.725\times10^{-3}\,T({}^\circ\text{C})$$

Check the answer in part a: $T({}^\circ\text{C}) = \dfrac{T({}^\circ\text{F}) - 32}{1.8}$

$$T = \frac{80-32}{1.8} = 26.67$$

$$C_p = 2.068 + (1.725\times10^{-3})(26.67) = 2.11\ \frac{\text{J}}{\text{g}\ {}^\circ\text{C}} \quad \text{(ok)}$$

* what do we mean by Btu ?

Btu is British thermal unit ; the energy required to raise 1 lbm of water 1°F is called 1 Btu

1 Cal ≡ the amount of energy required to raise 1 g of water 1 °C

** pressure ; P :

$$P = \frac{F}{A}$$ The pressure force F acts normal on surfaces

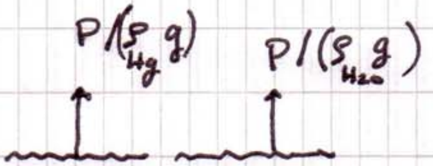
This definition will be revised in fluid mechanics course

* pressure can be expressed as a head of liquid with known density : $P = \rho g h$ h : Liquid head

$$h = \frac{P}{\rho g}$$

* units for pressure :

- SI : $\frac{N}{m^2} \equiv Pa$
- British : lb_f / ft^2
- Cgs : $dyne / cm^2$



other common units :

$psi \equiv \frac{lbf}{in^2}$; bar, atm, mm Hg, mm H_2O, torr

1atm = torr = 760 mm Hg = 101325 pa = 14.696 psi = ---- See Conversion table

* pressure measurement devices:

- Monometry : Barometer, Piezometer, U-shape manometers

- Mechanical devices such as Bourdon gage (guage)

* pressure at standard conditions: 1 atm

* Atmospheric gage, absolute, and Vacuum pressures:

$P_{abs} = P_g + P_{atm} \geqslant 0$ " absolute pressure P_{abs} must be +ve or zero "

$\Rightarrow P_g \geqslant -P_{atm}$ P_g : gage pressure

For $-P_{atm} \leqslant P_g < 0$ (we have vacuum)

the vacuum pressure is defined as: $P_{vac} = -P_g$

If $P_g = -P_{atm} \Rightarrow P_{abs} = 0$ (we have perfect vacuum)

Note that $P_g = P_{abs} - P_{atm}$: This means that

the gage pressure is the pressure relative to atmospheric pressure. why it is called gage pressure? Many pressure gages such as Bourdon gage are calibrated to read zero pressure when they are opened to atmosphere.

Ex: suppose that the vacuum pressure is 30 Kpa and the atmospheric pressure is 80 Kpa. Find the absolute pressure

$$P_{vac} = -P_g \Rightarrow P_g = -P_{vac} = -30 \text{ Kpa}$$

$$P_{abs} = P_g + P_{atm} = -30 + 80 = 50 \text{ Kpa}$$

* use always absolute pressure in thermodynamic relationships and also absolute temperature. such as ideal gas law.

* Unless you are told, assume that the given pressures are absolute.

* In British system of units when pressure is given in :

psia : it means $\frac{lbf}{in^2}$ (absolute)

psig : it means $\frac{lbf}{in^2}$ (absolute)

psi : for atmospheric pressure or pressure difference ΔP

ΔP (absolute) $=$ ΔP (gage)