Introduction to Chemical Engineering

Chapter 04

Describing Physical Quantities

4.1 Units

Units are used for expressing the dimensions.

Dimensions are:

- properties that can be measured such as length, mass, force, time, temperature and etc.
- properties that can be calculated by multiplying or dividing other dimensions, such as length/time, length^3, and mass/length^3.

Property	Dimension	Metric system		American engineering system
		SI system	cgs system	
Length	L	m	cm	ft
Mass	M	kg	g	lb_m
Time	T	s	s	s
Temperature	Θ	K	℃	℉

4.1 Units

SI (système international) system

Property	Dimension	Unit
Length	L	m
Mass	M	kg
Force	F	N
Time	T	s
Temperature	Θ	K

Property	Dimension	Unit
Volume	L^3	m^3
Density	$M\ L^{-1}$	$kg\ cm^{-3}$
Viscosity	$M\ L^{-1}\ T^{-1}$	$kg\ m^{-1}\ s^{-1}$
Pressure	$M\ L^{-1}\ T^{-2}$, $F\ L^{-2}$	$kg\ m^{-1}\ s^{-2}$
Energy	$M\ L^2\ T^{-2}$, $F\ L$	$kg\ m^2\ s^{-2}$

Prefixes for SI system

Multiple	Prefix	Symbol	Multiple	Prefix	Symbol
10^{-15}	femto	f	10^2	hecto	h
10^{-12}	pico	p	10^3	kilo	k
10^{-9}	nano	n	10^6	mega	M
10^{-6}	micro	μ	10^9	giga	G
10^{-3}	milli	m	10^{12}	tera	T
10^{-2}	centi	c	10^{15}	peta	P

4.1 Units

4.1.1 Conversion factors

- Definition: a conversion factor is a relationship expressed by an equation where the entries on both sides of the equation are the same quantity but expressed in different units.

Acceleration	$1\ m/s^2 = 3.2808\ ft/s^2$	$1\ ft/s^2 = 0.3048\ m/s^2$
Area	$1\ cm^2 = 0.155\ in^2$	$1\ in^2 = 6.4516\ cm^2$
	$1\ m^2 = 10.764\ ft^2$	$1\ ft^2 = 0.092903\ m^2$
Density	$1\ g/cm^3 = 62.43\ lb_m/ft^3$	$1\ lb_m/ft^3 = 0.016019\ g/cm^3$
	$1\ kg/m^3 = 0.06243\ lb_m/ft^3$	$1\ lb_m/ft^3 = 16.019\ kg/m^3$
Energy	$1\ J = 0.7376\ ft\ lb_f$	$1\ ft\ lb_f = 1.3558\ J$
	$1\ J = 9.478\times10^{-4}\ Btu$	$1\ Btu = 1055.0\ J = 778.1\ ft\ lb_f$
	$1\ J = 2.778\times10^{-7}\ kW\ hr$	$1\ kW\ hr = 3.600\times10^{6}\ J$
	$1\ J = 10^7\ ergs$	$1\ hp\ s = 550\ ft\ lb_f$
	$1\ J = 0.2390\ cal$	
Force	$1\ N = 0.22481\ lb_f$	$1\ lb_f = 4.4482\ N$
	$1\ N = 10^5\ dynes$	
Length	$1\ cm = 0.3937\ in$	$1\ in = 2.540\ cm$
	$1\ m = 3.2808\ ft$	$1\ ft = 12\ in = 0.3048\ m$
	$1\ km = 0.6214\ mi$ (statute)	$1\ yd = 3\ ft$
	$1\ km = 0.5400\ nmi$ (nautical)	$1\ mi$ (statute) $= 1609\ m = 5280\ ft$
		$1\ nmi$ (nautical) $= 1.8520\ km$
Mass	$1\ g = 0.03527\ oz$	$1\ oz = 28.35\ g$
	$1\ kg = 2.2046\ lb_m$	$1\ lb_m = 16\ oz = 453.6\ g$
	$1\ metric\ ton = 1000\ kg = 2205\ lb_m$	$1\ ton = 2000\ lb_m = 907.2\ kg$
Power	$1\ W = 0.7376\ ft\ lb_f/s$	$1\ ft\ lb_f/s = 1.3558\ W$
	$1\ W = 9.478\times10^{-4}\ Btu/s$	$1\ Btu/s = 1055.0\ W = 778.1\ ft\ lb_f/s$
	$1\ W = 1.341\times10^{-3}\ hp$	$1\ hp = 745.7\ W = 550\ ft\ lb_f/s$
Pressure	$1\ Pa = 1.450\times10^{-4}\ lb_f/in^2\ (psi)$	$1\ lb_f/in^2 = 6894.8\ Pa$
	$1\ Torr = 1\ mm\ Hg\ (@\ 0°C)$	$1\ atm = 101{,}325\ Pa$
		$1\ atm = 760\ mm\ Hg\ (@\ 0°C)$
		$1\ atm = 14.696\ lb_f/in^2\ (psi)$
		$1\ atm = 33.9\ ft\ H_2O\ (@\ 4°C)$
Temperature	$T(°C) = 5/9\,[T(°F) - 32]$	$T(°F) = 1.8\,T(°C) + 32$
	$T(K) = T(°C) + 273.15$	$T(R) = T(°F) + 459.67$
		$T(R) = 1.80\,T(K)$
Viscosity	$1\ cp = 6.7197\times10^{-4}\ lb_m/ft\ s$	$1\ lb_m/ft\ s = 1488.2\ cp = 14.882\ Poise$
Volume	$1\ cm^3 = 1\ mL = 0.06102\ in^3$	$1\ in^3 = 16.387\ cm^3$
	$1\ m^3 = 35.3145\ ft^3$	$1\ ft^3 = 0.028317\ m^3$
	$1\ m^3 = 1000\ liters$	$1\ ft^3 = 7.4805\ gal$
	$1\ m^3 = 264.17\ gal$	$1\ ft^3 = 28.317\ liters$
	$1\ L = 0.26417\ gal$	$1\ gal = 3.785\times10^{-3}\ m^3 = 3.785\ L$
Volume Flow	$1\ m^3/s = 15{,}850\ gal/min$	$1\ gal/min = 6.309\times10^{-5}\ m^3/s$
		$1\ gal/min = 2.228\times10^{-3}\ ft^3/s$
		$1\ ft^3/s = 448.8\ gal/min$

Ex) Conversion of 37759 inches to its equivalent in kilometers: $(37759\ in)\left(\frac{2.54\ cm}{1\ in}\right)\left(\frac{1\ m}{100\ cm}\right)\left(\frac{1\ km}{1000\ m}\right) = 0.959\ km$

4.1 Units

4.1.2 Moles

- Types of moles
  - gram-mole (*gmol*)

    : the amount of a species such that its mass in grams numerically equals its molecular weight (this amount is associated with Avogadro's number of molecules)

  - kilogram-mole (*kgmol*)

    : the amount of a species such that its mass in kilograms numerically equals its molecular weight

  - Pound-mole (*lbmol*)

    : the amount of a species such that its mass in pounds-mass numerically equals its molecular weight

4.1 Units

4.1.3 Molecular weight (MW)

For molecules, we use molecular weight (MW) rather than atomic weight. The molecular weight is simply the sum of the atomic weights for all of the atoms that make up the molecule.

For example, the MW of water (H_2O) is:

$$MW_{H_2O} = 2(1.01) + 16.00 = 18.02 = \frac{18.02\ g\ H_2O}{1\ gmol\ H_2O} = \frac{18.02\ kg\ H_2O}{1\ kgmol\ H_2O} = \frac{18.02\ lb_m\ H_2O}{1\ lbmol\ H_2O}$$

For example, what is the mass in grams of 10 gmols of water?

$$(10\ gmol\ H_2O)\left(\frac{18.02\ g\ H_2O}{1\ gmol\ H_2O}\right) = 180.2\ g$$

4.1 Units

4.1.4 Symbols

m = the mass of a quantity of material

m_A = the mass of a particular chemical species (in this case, species A), either as a pure material or within a mixture

n = the number of moles of a material

n_A = the number of moles of a particular chemical species (in this case, species A) either as a pure material or within a mixture

MW_A = the molecular weight of a particular chemical species (in this case, species A)

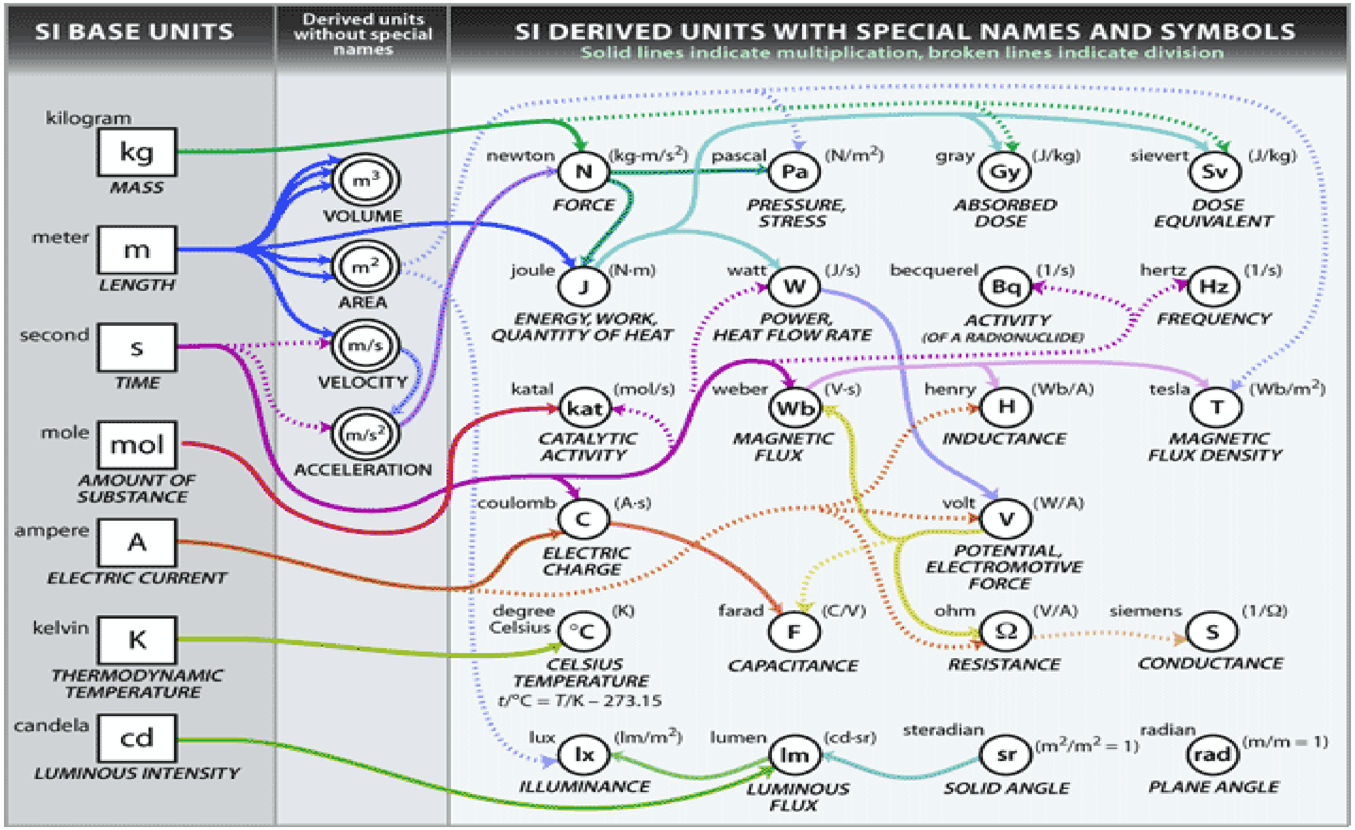
4.1 Units

Example 4.1

Common table sugar is sucrose, $C_{12}H_{22}O_{11}$. How many *lbmol* of sucrose are in a bag that has a mass of 100 lb_m? How many *kgmol*?

4.1 Units

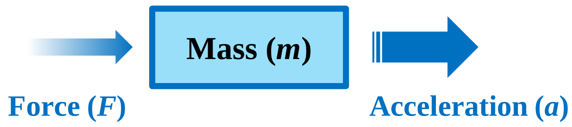
4.1.5 Combined and defined units



4.1 Units

4.1.6 Force

- A force (F) can cause an object with mass to change its velocity to accelerate.
- Derived from Newton's second law
- The force is the product of mass (m) and acceleration (a); $F = ma$.
- The weight is the product of mass (m) and Earth's gravity (g); $F_{weight} = mg$.



System	g	Defined Unit of Force
cgs	980.66 cm/s^2	1 $dyne \equiv 1\ g\ cm/s^2$
SI	9.8066 m/s^2	1 $Newton\ (N) \equiv 1\ kg\ m/s^2$
American	32.174 ft/s^2	1 $pound\text{-}force\ (lb_f) \equiv 32.174\ lb_m\ ft/s^2$

Example 4.1

An object has a mass equal to 8.41 kg. What is its weight (a) in Newtons (N) and (b) in pounds-force (lb_f)?

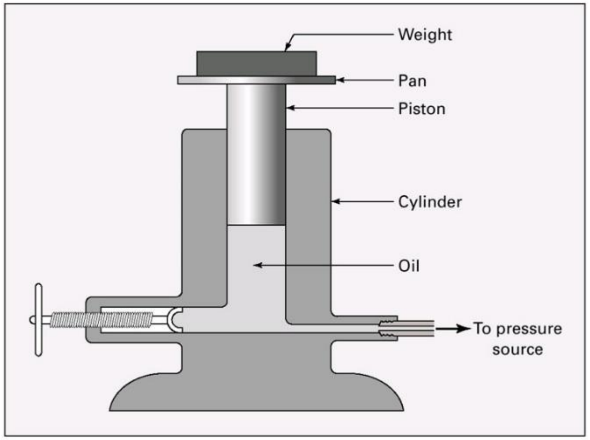
4.1 Units

4.1.7 Pressure

- A force (F) exerted per area (A)

System	Units of Pressure	Abbreviation	Defined Unit of Force
cgs	*Pascals*	*Pa*	$1\ Pa \equiv 1\ N/m^2 = 1\ g/cm\ s^2$
SI	*kiloPascals*	*kPa*	$1\ kPa \equiv 1000\ N/m^2 = 1000\ kg/m\ s^2$
American	lb_f/in^2	*psi*	$1\ lb_f/in^2 \equiv 4633\ lb_m/ft\ s^2$

- Dead-weight gauge



$$P = \frac{F}{A} = \frac{mg}{A} = \frac{Ah\rho g}{A} = h\rho g$$

m: mass of the piston, pan and weight

g: local acceleration of gravity

A: cross-sectional area of the piston

h: height of fluid

ρ: density of fluid

4.2 Some important variables

4.2.1 Density

- The mass of a unit volume of the material.

$$\rho = \frac{m}{V} \qquad or \qquad m = \rho V$$

- The density of water at room temperature

$$\rho_{water,25\,^{\circ}C} \approx 1.0\ g/cm^3 = 1000\ kg/m^3$$

- The density of air at room temperature

$$\rho_{air,25\,^{\circ}C} \approx 0.0012\ g/cm^3 = 1.2\ kg/m^3$$

4.2 Some important variables

4.2.2 Flow rate

- Three common types of flow rate
  - Mass flow rate (symbol $\dot{m}$)

    : the mass of a material that passes a reference plane within a unit time interval
  - Molar flow rate (symbol $\dot{n}$)

    : the number of moles of a material that passes a reference plane within a unit time interval
  - Volumetric flow rate (symbol $\dot{V}$)

    : the volume of a material that passes a reference plane within a unit time interval
- Conversion between mass flow rate, volumetric flow rate and density: $\dot{m} = \rho\dot{V}$

4.2 Some important variables

Example 4.4

The average flow rate of HCl produced by our company is 11,600 *L/hr* (see Chapter 3). Its density is approximately the same as that of water: 1000 kg/m^3, or 1 *kg/L*.

a. What is the equivalent of this flow rate in units of cm^3/s?

b. What is the mass flow rate for this stream in *kg/hr*?

4.2 Some important variables

4.2.3 Mixture composition

- Expressions of composition of species A in a mixture
  - Concentration of A: $c_A = \frac{moles\ of\ A}{volume\ of\ mixture} = \frac{n_A}{V} = \frac{molar\ flow\ rate\ of\ A}{volumetric\ flow\ rate\ of\ mixture} = \frac{\dot{n}_A}{\dot{V}}$
  - Mass fraction of A: $x_A = \frac{mass\ of\ A}{mass\ of\ mixture} = \frac{m_A}{m} = \frac{mass\ flow\ rate\ of\ A}{mass\ flow\ rate\ of\ mixture} = \frac{\dot{m}_A}{\dot{m}}$
  - Mole fraction of A: $y_A = \frac{moles\ of\ A}{moles\ of\ mixture} = \frac{n_A}{n} = \frac{molar\ flow\ rate\ of\ A}{molar\ flow\ rate\ of\ mixture} = \frac{\dot{n}_A}{\dot{n}}$
  - Mass percent of A = $100x_A$ commonly expresses as weight percent (*wt%*)
  - Mole percent of A = $100y_A$ (abbreviated mole%)
- Other expressions of mass and molar flow rates

$$\dot{m}_A = x_A\dot{m} = MW_A\dot{n}_A = MW_A y_A\dot{n} = MW_A c_A\dot{V} \qquad \dot{n}_A = \frac{\dot{m}_A}{MW_A} = \frac{x_A\dot{m}}{MW_A} = y_A\dot{n} = c_A\dot{V}$$

4.2 Some important variables

Example 4.5

For the acid-neutralization problem, the volumetric flow rate of the HCl solution coming from our manufacturing process is 11,600 *L/hr*, and the average concentration of HCl in that stream is 0.014 *M*, or 0.014 *gmol/L*. Based on this information and the answers in Example 4.4,

a. How many *gmol* of HCl are in 88 m^3 of the solution?

b. How many *gmol* of HCl are flowing from the process per minute (i.e., what is the molar flow rate) when the volumetric flow rate of the solution is 11,600 *L/hr*?

c. What is the mass fraction of HCl in the solution?

4.2 Some important variables

4.2.4 Conversion between mole fraction and mass fraction

- From “mole” fractions to “mass” fractions

Assume a basis of 100 moles → From the known mole fractions, calculate the number of moles of each species → Using the molecular weights, convert the moles into mass for each species → Compute the desired mass fractions or percentages

- From “mass” fractions to “mole” fractions

Assume a basis of 100 mass units → From the known mass fractions, calculate the mass of each species → Using the molecular weights, convert the mass into moles for each species → Compute the desired mole fractions or percentages

4.2 Some important variables

Example 4.6

One analysis of air produced the following approximate mole percentages:

$$N_2\text{: } 78.03\ \textit{mole\%}, \quad O_2\text{: } 20.99\ \textit{mole\%}, \quad \text{Ar: } 0.94\ \textit{mole\%}$$

What are the mass percentages of these components?

4.2 Some important variables

4.2.5 Dimensional consistency

- Equations that correctly describe physical phenomena must obey the rules of *dimensional consistency*:
  1. Terms that are added together (or subtracted) must have the same units. For example, in the equation $Q = ab + c^2$, the units of ab must be the same as those of c^2.
  2. Exponents must be unitless. Thus, if an exponent consists of several terms, the units of all those terms must cancel. For example, in the equation $y = x^{ab/c}$, the units in the term ab/c must all cancel out to leave no units.

Reading questions

Reading question 1.

"Pressure" was defined as force per area. In a particular situation, the pressure exerted on a certain surface is found to be 94,000 N/m^2 = 94,000 $kg/m\ s^2$. Identify the following parts of this expression of pressure:

all numerical value
all basic dimensions represented
all base units involved
any defined unit(s)

Homework problems

Homework problem 3.

A gas mixture has the following percentages by mass:

N_2: 70 %
O_2: 14 %
CO: 4 %
CO_2: 12 %

What are the mole percentages of the gases in the mixture?

Homework problems

Homework problem 6.

The exhaust gas coming from a coal-burning furnace (flue gas) usually contains sulfur in the form of SO_2, and when the gas is discharged into the atmosphere (which sometimes happens), the SO_2 can eventually react with oxygen and water to form sulfuric acid (H_2SO_4), hence, acid rain. The reaction is

$$SO_2 + \frac{1}{2}O_2 + H_2O \rightarrow H_2SO_4$$

The air around an old power plant has the following average composition

H_2SO_4: 0.1 mole%
O_2: 20.2 mole%
N_2: 77.9 mole%
H_2O: 1.8 mole%

Homework problems

Homework problem 9.

When a fluid flows from one location (“start”) to another location (“end”) under certain circumstances, the changes in fluid properties can be described by the Bernoulli equation, which is

$$\frac{P_{start} - P_{end}}{\rho} + \frac{1}{2}\alpha\left(v_{start}^2 - v_{end}^2\right) + g\left(z_{start} - z_{end}\right) = 0$$

where

α = a dimensionless correction factor
ρ = fluid density
P = fluid pressure
v = fluid velocity
z = fluid elevation
g = acceleration of gravity

Prove that this equation is dimensionally consistent in both the American engineering system and the metric system.
Hint: To handle the units in the pressure term, see Problem 8, and also remember the definitions of the various units of force and pressure shown in Table 4.3 and 4.4.