Almuthanna University
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مبادئ الهندسة الكيمياوية

المرحلة الاولى

اعداد

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Chemical Engineering Principles Outlines (Syllabus)

1. Engineering Calculations.
2. Units.
3. Dimensions.
4. Basis.
5. Temperature and Pressure.
6. Conversion, Yield, Selectivity.
7. Percent of Completion in Chemical Reactions.
9. Material Balance without Chemical Reaction.
10. Material Balance with Chemical Reaction.
11. Recycle.

References

1. Coulson & Richardson's, Chemical Engineering, Volume 1.
2. David M. Himmelblue and James B. Riggs, Basic Principles and Calculations in Chemical Engineering.
3. Ron Darby, Chemical Engineering Fluid Mechanics.
4. اسس حسابات الهندسة الكيمياوية ، الدكتور محمد صلاح العنبكي

Introduction

Students of chemical engineering soon discover that the data used are expressed in a great variety of different units, so that quantities must be converted into a common system before proceeding with calculations. Standardization has been largely achieved with the introduction of the *System International Unites***.** This system is now in general use in Europe and is rapidly being adopted throughout the rest of the world, including the USA where the initial inertia is now being overcome. Most of the physical properties determined in the laboratory will originally have been expressed in the (centimeter, gram, second "cgs") system.

The magnitude of any physical quantity is expressed as the product of two quantities; one is the magnitude of the unit and the other is the number of those units. Thus the distance between two points may be expressed as 1 m or as 100 cm or as 3.28 ft. The meter, centimeter, and foot are respectively the size of the units, and 1, 100, and 3,28 are the corresponding numbers of units. Since the physical properties of a system are interconnected by a series of mechanical and physical laws, it is convenient to regard certain quantities as basic and other quantities as derived.

DIMENSIONS AND UNITS

A. Dimensions

The dimensions of a quantity identify the physical character of that quantity, e.g., force (F), mass (M), length (L), time (t), temperature (T), electric charge (e), etc. On the other hand, ‘‘units’’ identify the reference scale by which the magnitude of the respective physical quantity is measured. Many different reference scales (units) can be defined for a given dimension; for example, the dimension of length can be measured in units of miles, centimeters, inches, meters, yards, angstroms, furlongs, light years, kilometers, etc.

There are two systems of fundamental dimensions in use (with their associated units), which are referred to as scientific and engineering systems. These systems differ basically in the manner in which the dimensions of force is defined. In both systems, mass, length, and time are fundamental dimensions.

Dimensions can be classified as either fundamental or derived. Fundamental dimensions cannot be expressed in terms of other dimensions and include length (L), time (t), temperature (T), mass (M), and/or force (F) (depending upon the system of dimensions used). Derived dimensions can be expressed in terms of fundamental dimensions, for example,

Area = L^2

Volume = L^3

B. Units

Several different sets of units are used in both scientific and engineering systems of dimensions. These can be classified as either metric (SI and cgs) or English (fps). Although the internationally accepted standard is the SI scientific system, English engineering units are still very common and will probably remain so for the foreseeable future. Therefore, the reader should at least master these two systems and become adept at converting between them. These systems are illustrated in Table (١). Note that there are two different English scientific systems, one in which M, L, and t are fundamental and F is derived, and another in which F, L, and t are fundamental and M is derived. In one system, mass (with the unit ‘‘slug’’) is fundamental; in the other, force (with the unit ‘‘poundal’’) is fundamental. However, these systems are archaic and rarely used in practice.

Table (1)

	Scientific				Engineering			
	L	M	F	g_c	L	M	F	g_c
English	ft	lb_m	poundal	1	ft	lb_m	lb_f	32.2
	ft	slug	lb_f	1				
Metric (SI)	m	kg	N	1	m	kg_m	kg_f	9.8
(cgs)	cm	g	dyn	1	cm	g_m	g_f	980

Conversion Factor Table

http://www.et.byu.edu/~jww8

Multiple inch **by** 2.54 **To Get** cm

This can also be written as: 1 inch = 2.54 cm

	Multiple	by	To Get
A	acre	43,560	ft^2
	ampere·hr (A·h)	3,600	coulomb (C)
	ångström (Å)	1x10^{-10}	m
	atm (atmosphere)	1.01325	bar
	atm, std	76.0	cm of Hg
	atm, std	760	mm of Hg at 0°C
	atm, std	33.90	ft of water
	atm, std	29.92	in of Hg at 30°F
	atm, std	14.696	lbf/in^2 abs (psia)
	atm, std	101.325	kPa
	atm, std	1.013x10^5	Pa
	atm, std	1.03323	kgf / cm^2
	atm, std	14.696	psia
B	bar	0.9869	atm, std
	bar	1x10^5	Pa
	Btu	778.169	ft·lbf
	Btu	1055.056	J
	Btu	5.40395	psia·ft^3
	Btu	2.928x10^{-4}	kWh
	Btu	1x10^{-5}	therm
	Btu / hr	1.055056	kJ / hr
	Btu / hr	0.216	ft·lbf / sec
	Btu / hr	3.929x10^{-4}	hp
	Btu / hr	0.2931	W
	Btu / lbm	2.326*	kJ / kg
	Btu / lbm	25,037	ft^2 / s^2
	Btu / lbm·R	4.1868	kJ / kg·K
	Btu / lbm·°F	4.1868	kJ / kg·°C
	Btu / lbmol·R	4.1868	kJ / kmol·K
C	cal (g-calorie)	3.968x10^{-3}	Btu
	cal	1.560x10^{-6}	hp·hr
	cal (IT calorie)	4.1868	J
	Calorie (Cal)	4.1868	kJ
	cal / sec	4.1868	W (watt)
	cm (centimeter)	0.03281	ft
	cm	0.3937	in
	cP (centipoise)	0.001	Pa·sec
	cSt (centistokes)	1x10^{-6}	m^2 / sec
D	degree	π/180	radian
	dyne	10	µN (micronewton)
E	eV (electronvolt)	1.602x10^{-19}	J
	erg	1x10^{-7}	J
F	ft (feet)	0.3048*	m
	ft	30.48	cm
	ft^2	2.2957x10^{-5}	acre
	ft^2	144	in^2
	ft^2	0.09290304*	m^2
	ft^3	7.481	gal (U.S.)
	ft^3	0.02832	m^3
	ft^3	28.317	L
	ft^3 / lbm	0.062428	m^3 / kg
	ft·lbf	1.285x10^{-3}	Btu
	ft·lbf	1.35582	J
	ft·lbf	3.766x10^{-7}	kWh
	ft·lbf	1.35582	N·m
	ft·lbf	0.324	calorie (g-cal)
	ft·lbf / sec	1.818x10^{-3}	hp
	ft / s^2	0.3048*	m / s^2
G	U.S. gallon (gal)	0.13368	ft^3
	gal	3.7854	L
	gal	3.7854x10^{-3}	m^3
	gal	231	in^3
	gal (U.K.)	1.201	gal (U.S.)
	gal (U.K.)	277.4	in^3
	gal / min (gpm)	0.002228	ft^3 / sec
	gamma (γ,Γ)	1x10^{-9}	tesla (T)
	gauss	1x10^{-4}	T
	gram (g)	2.205x10^{-3}	lbm
	g / cm^3	1	1 kg / L
	g / cm^3	1000	kg / m^3
	g / cm^3	62.428	lbm / ft^3
	g / cm^3	1.940	slug / ft^3
	g / cm^3	0.036127	lbm / in^3
H	hectare	1x10^4	m^2
	hectare	2.47104	acres
	hp (horsepower)	42.41	Btu / min
	hp	0.7068	Btu / sec
	hp	2544.5	Btu / hr
	hp	745.70	W (watt)
	hp	0.74570	kW
	hp	33,000	ft·lbf / min
	hp	550	ft·lbf / sec
	hp·hr	2544	Btu
	hp·hr	1.98x10^6	ft·lbf
	hp·hr	2.68x10^6	J
	in	2.54*	cm
	in of Hg	0.0334	atm
	in of Hg	13.60	in of water
	in of Hg	3.387	kPa
	in of water	0.0736	in of Hg
	in of water	0.0361	lbf / in^2 (psi)
	in of water	0.002458	atm
J	J (joule)	9.4782x10^{-4}	Btu
	J	6.2415x10^{18}	eV
	J	0.73756	ft·lbf
	J	1	N·m
	J	1x10^7	ergs
	J / s	1	W
K	kg (kilogram)	2.2046226	lbm (pound mass)
	kg	0.068522	slug
	kg	1x10^{-3}	metric ton
	kg / m^3	0.062428	lbm / ft^3
	kgf	9.80665	newton (N)
	kip	1000	lbf
	kip	4448	N
	kJ	1	1 kPa·m^3
	kJ	1000	N·m
	kJ	0.94782	Btu
	kJ	737.56	ft·lbf
	kJ / kg	1000	m^2 / s^2
	kJ / kg	0.42992	Btu / lbm
	kJ / kg·K	0.23885	Btu / lbm·°R
	kJ / kg·°C	1	kJ / kg·K
	kJ / kg·°C	1	J / g·°C
	kJ / kg·°C	0.23885	Btu / lbm·°F
	kJ / kg·°C	0.23885	Btu / lbm·R
	km	3280.8	ft
	km	0.6214	mi
	km/hr	0.6214	mi / hr (mph)
	km/hr	0.2778	m/s
	km/hr	0.9113	ft/s
	kPa (kilopascal)	9.8693x10^{-3}	atm
	kPa	0.14504	lbf / in^2 (psi)
	kW	3412.14	Btu / hr
	kW	0.9478	Btu / sec
	kW	737.56	lbf·ft / sec
	kW	1.341	hp
	kWh (kW-hour)	3412.14	Btu
	kWh	1.341	hp·hr
	kWh	3600	kJ
L	L (liter)	0.03531	ft^3
	L	61.02	in^3
	L	0.2642	gal (U.S.)
	L	0.001	m^3
	L / s	2.119	ft^3 / min (cfm)
	L / s	15.85	gal / min (gpm)
	lbf (pound force)	32.174	lbm·ft / s^2
	lbf	4.44822	N
	lbf	32.17	poundals
	lbf / in^2 (psi)	0.06805	atm
	lbf / in^2	2.307	ft water
	lbf / in^2	2.036	in Hg
	lbf / in^2	6894.757	Pa
	lbm	0.45359237*	kg
	lbm	0.031081	slug
	lbm / in^3	1728	lbm / ft^3
	lbm / ft^3	0.016018	g / cm^3
	lbm / ft^3	16.018	kg / m^3
M	m (meter)	3.28083	ft
	m	1.0926	yard
	m	39.370	in
	m^2	1550	in^2
	m^2	10.764	ft^2
	m^3	1x10^6	cm^3 (cc)
	m^3	35.315	ft^3
	m^3	264.17	gal (U.S.)
	m^3	1000	L
	m^3 / kg	16.02	ft^3 / lbm
	m / s	196.8	ft / min
	m / s	3.60	km / h
	m / s	3.2808	ft / s
	m / s	2.237	mi / h (mph)
	m / s^2	3.2808	ft / s^2
	metric ton	1000	kg
	mil	0.001	in
	mi (mile)	5280	ft
	mi	1.6093	km
	mi^2 (square mile)	640	acres
	mph (mile/hour)	1.6093	km / hr
	mph	88.0	ft / min (fpm)
	mph	1.467	ft / s
	mph	0.4470	m / s
	micron	1x10^{-6}	m
	mm of Hg	1.316x10^{-3}	atm
	mm of Hg	0.1333	kPa
	mm of water	9.678x10^{-5}	atm
N	N (newton)	1	kg·m / s^2
	N	1x10^5	dyne
	µN (microN)	0.1	dyne
	N	0.22481	lbf
	N·m	0.7376	ft·lbf
	N·m	1	J
P	Pa (pascal)	1	N / m^2
	Pa	1.4504x10^{-4}	lbf / in^2 (psia)
	Pa	0.020886	lbf / ft^2
	Pa	9.869x10^{-6}	atm
	Pa·s	10	poise
	psi (pounds per square inch) --- see lbf / in^2		
R	radian	180/π	degree
S	short ton	2000	lbm
	short ton	907.1847	kg
	slug	32.174	lbm
	slug	14.5939	kg
	slug / ft^3	0.5154	g / cm^3
	stokes	1x10^{-4}	m^2 / s
T	therm	1x10^5	Btu
	ton of refrigeration	200	Btu / min
W	W (watt)	3.4121	Btu / hr
	W	0.7376	ft·lbf / sec
	W	1.341x10^{-3}	hp
	W	1	J / s
	W / cm^2	1x10^4	W / m^2
	W / cm^3	1x10^6	W / m^3
	W / m^2	0.3171	Btu / (h·ft^2)
	W / m^3	0.09665	Btu / (h·ft^3)
	W / m·°C	1	W / m·K
	W / m·°C	0.57782	Btu / (h·ft·°F)
	W / (m^2·°C)	1	W / (m^2·K)
	W / (m^2·°C)	0.17612	Btu / (h·ft^2·°F)
	weber / m^2	10,000	gauss

* The exact conversion between metric and English.

TEMPERATURE

$T(\text{K}) = T(°\text{C}) + 273.15$

$T(\text{R}) = T(°\text{F}) + 459.67$

$T(°\text{F}) = 1.8\ T(°\text{C}) + 32$

SOME IMPORTANT CONSTANTS

Atomic Mass Unit (u)	=	1.66054x10^{-27} kg
Avogadro's number (N_A)	=	6.02213x10^{23} particles/mol
Boltzmann's constant (k_B)	=	1.38065x10^{-23} J / K
electron charge (e)	=	-1.6022x10^{-19} C
electron mass (m_e)	=	9.10939x10^{-31} kg
proton mass (m_p)	=	1.6726x10^{-27} kg
Gas Constant (R)	=	8314 J / kmol·K
Gravitational Constant (G)	=	6.672x10^{-11} N·m^2 / kg^2
Gravity (mean)	=	9.8067 (9.81) m / s^2
Planck's constant (h)	=	6.6260x10^{-34} J·s
Speed of Light (c)	=	2.99792458x10^8 m/s (exact)

SI PREFIXES

yocto (10^{-24}), zepto (10^{-21}), atto (10^{-18}), femto (10^{-15}), pico (10^{-12}), nano (10^{-9}), micro (10^{-6}), milli (10^{-3}), centi (10^{-2}), deci (10^{-1}), deka (10^1), hecto (10^2), kilo (10^3), mega (10^6), giga (10^9), tera (10^{12}), peta (10^{15}), exa (10^{18}), zetta (10^{21}), yotta (10^{24})

UNITS CONVERSION TABLES

Overview

These conversion tables are provided for your reference.

Units Conversion Tables

Table 1	Multiples and Submultiples of SI Units
Table 2	Length Units
Table 3	Area Units
Table 4	Volume Units
Table 5	Mass Units
Table 6	Density Units
Table 7	Volumetric Liquid Flow Units
Table 8	Volumetric Gas Flow Units
Table 9	Mass Flow Units
Table 10	High Pressure Units
Table 11	Low Pressure Units
Table 12	Speed Units
Table 13	Torque Units
Table 14	Dynamic Viscosity Units
Table 15	Kinematic Viscosity Units
Table 16	Temperature Conversion Formulas

Table 1: Multiples and Submultiples of SI units

Prefix	Symbol	Multiplying Factor	
exa	E	10^{18}	1 000 000 000 000 000 000
peta	P	10^{15}	1 000 000 000 000 000
tera	T	10^{12}	1 000 000 000 000
giga	G	10^{9}	1 000 000 000
mega	M	10^{6}	1 000 000
kilo	k	10^{3}	1 000
hecto*	h	10^{2}	100
deca*	da	10	10
deci*	d	10^{-1}	0.1
centi	c	10^{-2}	0.01
milli	m	10^{-3}	0.001
micro	u	10^{-6}	0.000 001
nano	n	10^{-9}	0.000 000 001
pico	p	10^{-12}	0.000 000 000 001
femto	f	10^{-15}	0.000 000 000 000 001
atto	a	10^{-18}	0.000 000 000 000 000 001

* these prefixes are not normally used

Table 2: Length Units

Millimeters	Centimeters	Meters	Kilometers	Inches	Feet	Yards	Miles
mm	cm	m	km	in	ft	yd	mi
1	0.1	0.001	0.000001	0.03937	0.003281	0.001094	6.21e-07
10	1	0.01	0.00001	0.393701	0.032808	0.010936	0.000006
1000	100	1	0.001	39.37008	3.28084	1.093613	0.000621
1000000	100000	1000	1	39370.08	3280.84	1093.613	0.621371
25.4	2.54	0.0254	0.000025	1	0.083333	0.027778	0.000016
304.8	30.48	0.3048	0.000305	12	1	0.333333	0.000189
914.4	91.44	0.9144	0.000914	36	3	1	0.000568
1609344	160934.4	1609.344	1.609344	63360	5280	1760	1

Table 3: Area Units

Millimeter square	Centimeter square	Meter square	Inch square	Foot square	Yard square
mm^2	cm^2	m^2	in^2	ft^2	yd^2
1	0.01	0.000001	0.00155	0.000011	0.000001
100	1	0.0001	0.155	0.001076	0.00012
1000000	10000	1	1550.003	10.76391	1.19599
645.16	6.4516	0.000645	1	0.006944	0.000772
92903	929.0304	0.092903	144	1	0.111111
836127	8361.274	0.836127	1296	9	1

Table 4: Volume Units

Centimeter cube	Meter cube	Liter	Inch cube	Foot cube	US gallons	Imperial gallons	US barrel (oil)
cm^3	m^3	ltr	in^3	ft^3	US gal	Imp. gal	US brl
1	0.000001	0.001	0.061024	0.000035	0.000264	0.00022	0.000006
1000000	1	1000	61024	35	264	220	6.29
1000	0.001	1	61	0.035	0.264201	0.22	0.00629
16.4	0.000016	0.016387	1	0.000579	0.004329	0.003605	0.000103
28317	0.028317	28.31685	1728	1	7.481333	6.229712	0.178127
3785	0.003785	3.79	231	0.13	1	0.832701	0.02381
4545	0.004545	4.55	277	0.16	1.20	1	0.028593
158970	0.15897	159	9701	6	42	35	1

Table 5: Mass Units

Grams	Kilograms	Metric tonnes	Short ton	Long ton	Pounds	Ounces
g	kg	tonne	shton	Lton	lb	oz
1	0.001	0.000001	0.000001	9.84e-07	0.002205	0.035273
1000	1	0.001	0.001102	0.000984	2.204586	35.27337
1000000	1000	1	1.102293	0.984252	2204.586	35273.37
907200	907.2	0.9072	1	0.892913	2000	32000
1016000	1016	1.016	1.119929	1	2239.859	35837.74
453.6	0.4536	0.000454	0.0005	0.000446	1	16
28	0.02835	0.000028	0.000031	0.000028	0.0625	1

Table 6: Density Units

Gram/milliliter	Kilogram/meter cube	Pound/foot cube	Pound/inch cube
g/ml	kg/m^3	lb/ft^3	lb/in^3
1	1000	62.42197	0.036127
0.001	1	0.062422	0.000036
0.01602	16.02	1	0.000579
27.68	27680	1727.84	1

Table 7: Volumetric Liquid Flow Units

Liter/second	Liter/minute	Meter cube/hour	Foot cube/minute	Foot cube/hour	US gallons/minute	US barrels (oil)/day
L/sec	L/min	M^3/hr	ft^3/min	ft^3/hr	gal/min	US brl/d
1	60	3.6	2.119093	127.1197	15.85037	543.4783
0.016666	1	0.06	0.035317	2.118577	0.264162	9.057609
0.277778	16.6667	1	0.588637	35.31102	4.40288	150.9661
0.4719	28.31513	1.69884	1	60	7.479791	256.4674
0.007867	0.472015	0.02832	0.01667	1	0.124689	4.275326
0.06309	3.785551	0.227124	0.133694	8.019983	1	34.28804
0.00184	0.110404	0.006624	0.003899	0.2339	0.029165	1

Table 8: Volumetric Gas Flow Units

Normal meter cube/hour	Standard cubic feet/hour	Standard cubic feet/minute
Nm^3/hr	scfh	scfm
1	35.31073	0.588582
0.02832	1	0.016669
1.699	59.99294	1

Table 9: Mass Flow Units

Kilogram/hour	Pound/hour	Kilogram/second	Ton/hour
kg/h	lb/hour	kg/s	t/h
1	2.204586	0.000278	0.001
0.4536	1	0.000126	0.000454
3600	7936.508	1	3.6
1000	2204.586	0.277778	1

Table 10: High Pressure Units

Bar	Pound/square inch	Kilopascal	Megapascal	Kilogram force/ centimeter square	Millimeter of mercury	Atmospheres
bar	psi	kPa	MPa	kgf/cm^2	mm Hg	atm
1	14.50326	100	0.1	1.01968	750.0188	0.987167
0.06895	1	6.895	0.006895	0.070307	51.71379	0.068065
0.01	0.1450	1	0.001	0.01020	7.5002	0.00987
10	145.03	1000	1	10.197	7500.2	9.8717
0.9807	14.22335	98.07	0.09807	1	735.5434	0.968115
0.001333	0.019337	0.13333	0.000133	0.00136	1	0.001316
1.013	14.69181	101.3	0.1013	1.032936	759.769	1

Table 11: Low Pressure Units

Meter of water	Foot of water	Centimeter of mercury	Inches of mercury	Inches of water	Pascal
mH_2O	ftH_2O	cmHg	inHg	inH_2O	Pa
1	3.280696	7.356339	2.896043	39.36572	9806
0.304813	1	2.242311	0.882753	11.9992	2989
0.135937	0.445969	1	0.39368	5.351265	1333
0.345299	1.13282	2.540135	1	13.59293	3386
0.025403	0.083339	0.186872	0.073568	1	249.1
0.000102	0.000335	0.00075	0.000295	0.004014	1

Table 12: Speed Units

Meter/second	Meter/minute	Kilometer/hour	Foot/second	Foot/minute	Miles/hour
m/s	m/min	km/h	ft/s	ft/min	mi/h
1	59.988	3.599712	3.28084	196.8504	2.237136
0.01667	1	0.060007	0.054692	3.281496	0.037293
0.2778	16.66467	1	0.911417	54.68504	0.621477
0.3048	18.28434	1.097192	1	60	0.681879
0.00508	0.304739	0.018287	0.016667	1	0.011365
0.447	26.81464	1.609071	1.466535	87.99213	1

Table 13: Torque Units

Newton meter	Kilogram force meter	Foot pound	Inch pound
Nm	kgfm	ftlb	inlb
1	0.101972	0.737561	8.850732
9.80665	1	7.233003	86.79603
1.35582	0.138255	1	12
0.112985	0.011521	0.083333	1

Table 14: Dynamic Viscosity Units

Centipoise*	Poise	Pound/foot·second
cp	poise	lb/(ft·s)
1	0.01	0.000672
100	1	0.067197
1488.16	14.8816	1

Table 15: Kinematic Viscosity Units

Centistoke*	Stoke	Foot square/second	meter square/second
cs	St	ft^2/s	m^2/s
1	0.01	0.000011	0.000001
100	1	0.001076	0.0001
92903	929.03	1	0.092903
1000000	10000	10.76392	1

*note: centistokes x specific gravity = centipoise

Table 16: Temperature Conversion Formulas

Degree Celsius (°C)	(°F - 32) x 5/9
	(K - 273.15)
Degree Fahrenheit (°F)	(°C x 9/5) + 32
	(1.8 x K) - 459.67
Kelvin (K)	(°C + 273.15)
	(°F + 459.67) ÷ 1.8

1.2 THE MOLE UNIT

Your objectives in studying this section are to be able to:

1. Define a kilogram mole, pound mole, and gram mole.
2. Convert from moles to mass and the reverse for any chemical compound given the molecular weight.
3. Calculate molecular weights from the molecular formula.

What is a mole? The best answer is that a **mole** is a certain number of molecules, atoms, electrons, or other specified types of particles.[4] In particular, the 1969 International Committee on Weights and Measures approved the mole (symbol mol in the SI system) as being "the amount of a substance that contains as many elementary entities as there are atoms in 0.012 kg of carbon 12." Thus in the SI system the mole contains a different number of molecules than it does in the American engineering system. In the SI system a mole has about 6.023×10^{23} molecules; we shall call this a *gram mole* (symbol *g mol*) to avoid confusion even though in the SI system of units the official designation is simply mole (abbreviated mol). We can thereby hope to avoid the confusion that could occur with the American engineering system *pound mole* (abbreviated *lb mol*), which has $6.023 \times 10^{23} \times 453.6$ molecules. Thus a pound mole of a substance has more mass than does a gram mole of the substance.

Here is another way to look at the mole unit. To convert the number of moles to mass, we make use of the **molecular weight**—the mass per mole:

$$\text{the g mol} = \frac{\text{mass in g}}{\text{molecular weight}} \tag{1.4}$$

$$\text{the lb mol} = \frac{\text{mass in lb}}{\text{molecular weight}} \tag{1.5}$$

or

$$\text{mass in g} = (\text{mol. wt.})(\text{g mol}) \tag{1.6}$$

$$\text{mass in lb} = (\text{mol. wt.})(\text{lb mol}) \tag{1.7}$$

Furthermore, there is no reason why you cannot carry out computations in terms of ton moles, kilogram moles, or any corresponding units if they are defined analogously to Eqs. (1.4) and (1.5) even if they are not standard units. If you read

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about a unit such as a kilomole (kmol) without an associated mass specification, or a kg mol, assume that it refers to the SI system and 10^3 g mol.

1.3-1 Density

Density is the ratio of mass per unit volume, as, for example, kg/m^3 or lb/ft^3. It has both a numerical value and units. To determine the density of a substance, you must find both its volume and its mass. If the substance is a solid, a common method to determine its volume is to displace a measured quantity of inert liquid. For example, a known weight of a material can be placed into a container of liquid of known weight and volume, and the final weight and volume of the combination measured. The density (or specific gravity) of a liquid is commonly measured with a hydrometer (a known weight and volume is dropped into the liquid and the depth to which it penetrates into the liquid is noted) or a Westphal balance (the weight of a known slug is compared in the unknown liquid with that in water). Gas densities are quite difficult to measure; one device used is the Edwards balance, which compares the weight of a bulb filled with air to the same bulb when filled with the unknown gas.

In most of your work using liquids and solids, density will not change very much with pressure, but for precise measurements for common substances you can always look up in a handbook the variation of density with pressure. The change in density with temperature is illustrated in Fig. 1.1 for liquid water and liquid ammo-

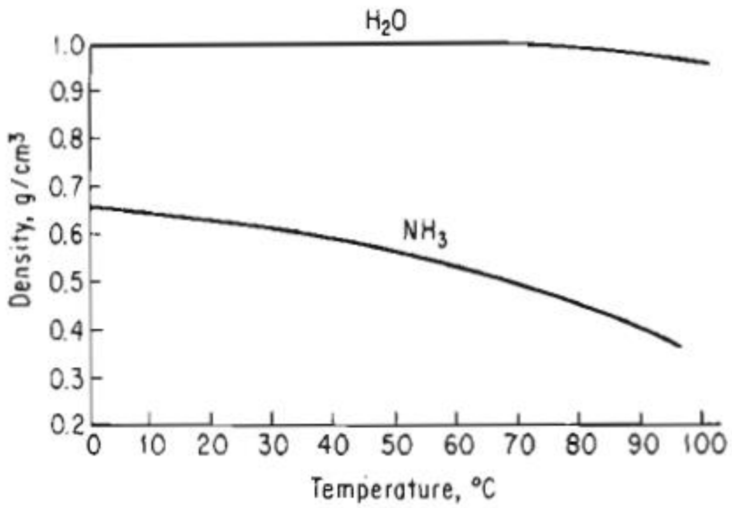


Figure 1.1 Densities of liquid H_2O and NH_3 as a function of temperature.

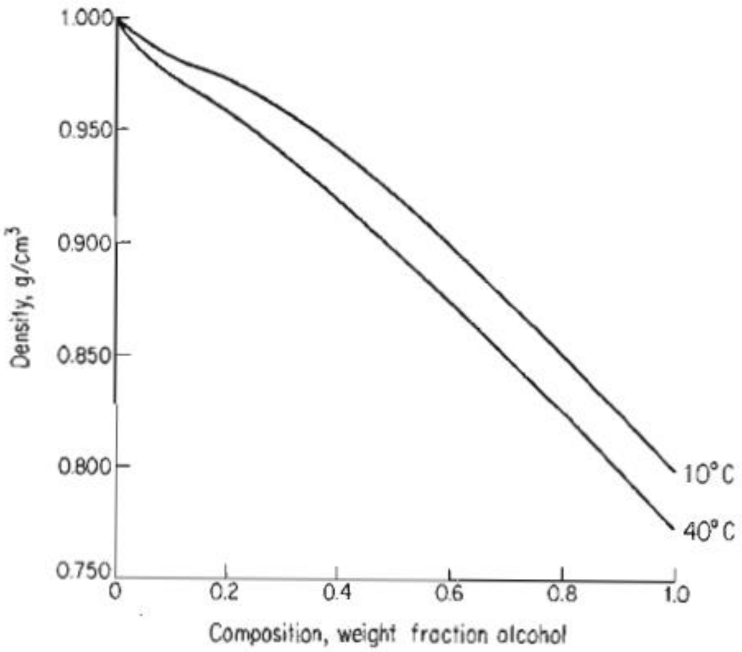


Figure 1.2 Density of a mixture of ethyl alcohol and water as a function of composition.

nia. Figure 1.2 illustrates how density also varies with composition. In the winter you may put antifreeze in your car radiator. The service station attendant checks the concentration of antifreeze by measuring the specific gravity and, in effect, the density of the radiator solution after it is mixed thoroughly. He has a little thermometer in his hydrometer kit in order to be able to read the density corrected for temperature.

1.3-2 Specific Gravity

Specific gravity is commonly thought of as a dimensionless ratio. Actually, it should be considered as the ratio of two densities—that of the substance of interest, A, to that of a reference substance. In symbols:

$$\text{sp gr} = \textbf{specific gravity} = \frac{(\text{lb/ft}^3)_A}{(\text{lb/ft}^3)_{\text{ref}}} = \frac{(\text{g/cm}^3)_A}{(\text{g/cm}^3)_{\text{ref}}} = \frac{(\text{kg/m}^3)_A}{(\text{kg/m}^3)_{\text{ref}}} \tag{1.8}$$

The reference substance for liquids and solids is normally water. Thus the specific gravity is the ratio of the density of the substance in question to the density of water. The specific gravity of gases frequently is referred to air, but may be referred to other gases, as discussed in more detail in Chap. 3. Liquid density can be considered to be nearly independent of pressure for most common calculations, but, as indicated in Fig. 1.1 it varies somewhat with temperature; therefore, to be very precise when referring to specific gravity, state the temperature at which each density is chosen. Thus

$$\text{sp gr} = 0.73\,\frac{20^\circ}{4^\circ}$$

can be interpreted as follows: the specific gravity when the solution is at 20°C and the reference substance (water) is at 4°C is 0.73. Since the density of water at 4°C is very close to 1.0000 g/cm^3 in the SI system, the numerical values of the specific gravity and density in this system are essentially equal. Since densities in the American engineering system are expressed in lb/ft^3 and the density of water is about 62.4 lb/ft^3, it can be seen that the specific gravity and density values are not numerically equal in the American engineering system.

In the petroleum industry the specific gravity of petroleum products is usually reported in terms of a hydrometer scale called °API. The equation for the API scale is

$$°API = \frac{141.5}{\text{sp gr}\frac{60°}{60°}} - 131.5 \tag{1.9}$$

or

$$\text{sp gr}\frac{60°}{60°} = \frac{141.5}{°API + 131.5} \tag{1.10}$$

The volume and therefore the density of petroleum products vary with temperature, and the petroleum industry has established 60°F as the standard temperature for volume and API gravity. The °API is being phased out as SI units are accepted for densities.

There are many other systems of measuring density and specific gravity that are somewhat specialized; for example, the Baumé (°Be) and the Twaddell (°Tw) systems. Relationships among the various systems of density may be found in standard reference books.

1.3-3 Specific Volume

The specific volume of any compound is the inverse of the density, that is, the volume per unit mass or unit amount of material. Units of specific volume might be ft^3/lb$_m$, ft^3/lb mole, cm^3/g, bbl/lb$_m$, m^3/kg, or similar ratios.

1.3-4 Mole Fraction and Mass (Weight) Fraction

Mole fraction is simply the moles of a particular substance divided by the total number of moles present. This definition holds for gases, liquids, and solids. Similarly, the **mass (weight) fraction** is nothing more than the **mass (weight)** of the substance divided by the total mass (weight) of all substances present. Although the mass fraction is what is intended to be expressed, ordinary engineering usage employs the term **weight fraction.** Mathematically, these ideas can be expressed as

$$\text{mole fraction of } A = \frac{\text{moles of } A}{\text{total moles}} \tag{1.11}$$

$$\text{mass (weight) fraction of } A = \frac{\text{mass (weight) of } A}{\text{total mass (weight)}} \tag{1.12}$$

Mole percent and weight percent are the respective fractions times 100.

Problem 1.1A

Convert the following quantities to the ones designated :

a. 42 ft^2/hr to cm^2/s.
b. 25 psig to psia.
c. 100 Btu to hp-hr.

Solution

a. $$\frac{42.0\ ft^2}{hr}\left(\frac{1.0\ m}{3.2808\ ft}\right)^2\frac{10^4 cm^2}{1.0\ m^2}\ \frac{1\ hr}{3600\ s} = \mathbf{10.8\ cm^2/s}$$

b. $$100\ Btu\ \frac{3.93\times 10^{-4}\ hp\text{-}hr}{1\ Btu} = \mathbf{3.93\times 10^{-2}\ hp\text{-}hr}$$

c. $$80.0\ lb_f\ \frac{32.174\ (lb_m)(ft)}{(lb_f)(s)^2}\ \frac{1\ kg}{2.20\ lb_m}\ \frac{1\ m}{3.2808\ ft}\ \frac{1\ N}{1\ (kg)(m)(s)^{-2}} = \mathbf{356\ N}$$

Problem 1.1 B

Convert the ideal gas constant : $R = 1.987\ \frac{cal}{(gmol)(K)}$ to $\frac{Btu}{(lb\ mol)(°R)}$

Solution

$$\frac{1.987\ cal}{(gmol)(K)}\ \frac{1\ Btu}{252\ cal}\ \frac{454\ gmol}{1\ lb\ mol}\ \frac{1K}{1.8\ °R} = \mathbf{1.98\ \frac{Btu}{(lb\ mol)(°R)}}$$

Problem 1.1 C

Mass flow through a sonic nozzle is a function of gas pressure and temperature. For a given pressure p and temperature T, mass flow rate through the nozzle is given by

$m = 0.0549\ p\ /(T)^{0.5}$ where m is in lb/min, p is in psia and T is in °R

a. Determine what the units for the constant 0.0549 are.
b. What will be the new value of the constant, now given as 0.0549, if the variables in the equation are to be substituted with SI units and m is calculated in SI units.

Solution

a. Calculation of the constant.

The first step is to substitute known units into the equation.

$$\frac{lb_m}{min} = 0.0549 \frac{lb_f}{(in^2)(°R)^{0.5}}$$

We want to find a set of units that convert units on the right hand side of the above expression to units on the left hand side of the expression. Such a set can be set up directly by multiplication.

$$\frac{lb_f}{(in^2)(°R)^{0.5}} \left| \frac{(lb_m)(in)^2(°R)^{0.5}}{(min)(lb_f)} \right. \;\text{------>}\; \frac{(lb_m)}{(min)}$$

Units for the constant 0.0549 are $\frac{(lb_m)(in)^2(°R)^{0.5}}{(min)(lb_f)}$

b. To determine the new value of the constant, we need to change the units of the constant to appropriate SI units using conversion factors.

$$\frac{0.0549\ (lb_m)\,(in^2)\,(°R)^{0.5}}{(lb_f)\,(min)} \left| \frac{(0.454\ kg)}{(1\ lb_m)} \right| \frac{(14.7\ lb_f/in^2)}{(101.3 \times 10^3\ N/m^2)} \left| \frac{(1\ min)}{(60\ s)} \right| \frac{(1K)^{0.5}}{(1.8\ °R)^{0.5}} \left| \frac{(p)}{(T)^{0.5}} \right.$$

$$\mathbf{m = 4.49 \times 10^{-8}\ (m)\ (s)\ (K)^{0.5}\ \frac{(p)}{(T)^{0.5}}}$$

Substituting pressure and temperature in SI units

$$m = 4.49 \times 10^{-8}\ (m)\ (s)\ (K)^{0.5}\ \frac{(p)\ (N/m^2)}{(T)^{0.5}\ (K)^{0.5}} \left| \frac{1\ kg/(m)(s)^2}{1\ N/m^2} \right.$$

$$\mathbf{m\ \frac{(kg)}{(s)} = 4.49 \times 10^{-8} \frac{(p)}{(T)^{0.5}}}$$ where p is in N/m^2 and T is in K

Problem 1.1 D

An empirical equation for calculating the inside heat transfer coefficient, h_i, for the turbulent flow of liquids in a pipe is given by:

$$h_i = \frac{0.023\ G^{0.8}\ K^{0.67}\ Cp^{0.33}}{D^{0.2}\ \mu^{0.47}}$$

where h_i = heat transfer coefficient, Btu/(hr)(ft)^2(°F)
G = mass velocity of the liquid, lb_m/(hr)(ft)^2
K = thermal conductivity of the liquid, Btu/(hr)(ft)(°F)
C_p = heat capacity of the liquid, Btu/(lb_m)(°F)
μ = Viscosity of the liquid, lb_m/(ft)(hr)
D = inside diameter of the pipe, (ft)

a. Verify if the equation is dimensionally consistent.
b. What will be the value of the constant, given as 0.023, if all the variables in the equation are inserted in SI units and h_i is in SI units.

Solution

a. First we introduce American engineering units into the equation:

$$h_i = \frac{0.023[(lb_m)/(ft)^2(hr)]^{0.80}\ [Btu/(hr)(ft)(°F)]^{0.67}\ [Btu/(lb_m)(°F)]^{0.33}}{(ft)^{0.2}\qquad [lb_m/(ft)(hr)]^{0.47}}$$

Next we consolidate like units

$$h_i = \frac{0.023(Btu)^{0.67}\quad (lb_m)^{0.8}}{[(lb_m)^{0.33}(lb_m)^{0.47}]}\left|\frac{(ft)^{0.47}}{[(ft)^{1.6}(ft)^{0.67}(ft)^{0.2}]}\right|\frac{(1)}{[(°F)^{0.67}(°F)^{0.33}]}\left|\frac{(hr)^{0.47}}{[(hr)^{0.8}(hr)^{0.67}]}\right.$$

$$h_i = 0.023 \quad \frac{Btu}{(hr)(ft)^2\ (°F)}$$

The equation is dimensionally consistent.

b. The constant 0.023 is dimensionless; a change in units of the equation parameters will not have any effect on the value of this constant.

Problem 1.2 A

Calcium carbonate is a naturally occuring white solid used in the manufacture of lime and cement. Calculate the number of lb mols of calcium carbonate in:

a. 50 g mol of $CaCO_3$.
b. 150 kg of $CaCO_3$.
c. 100 lb of $CaCO_3$.

Solution

a. $$\frac{50\ \text{g mol } CaCO_3}{} \left| \frac{100\ \text{g } CaCO_3}{1\ \text{g mol } CaCO_3} \right| \frac{1\ \text{lb } CaCO_3}{454\ \text{g } CaCO_3} \left| \frac{1\ \text{lb mol } CaCO_3}{100\ \text{lb } CaCO_3} \right. = \mathbf{0.11\ lb\ mol}$$

b. $$\frac{150\ \text{kg } CaCO_3}{} \left| \frac{2.205\ \text{lb } CaCO_3}{1\ \text{kg } CaCO_3} \right| \frac{1\ \text{lb mol } CaCO_3}{100\ \text{lb } CaCO_3} = \mathbf{3.30\ lb\ mol}$$

c. $$\frac{100\ \text{lb } CaCO_3}{} \left| \frac{1\ \text{lb mol } CaCO_3}{100\ \text{lb } CaCO_3} \right. = \mathbf{1.00\ lb\ mol\ CaCO_3}$$

Problem 1.2 B

Silver nitrate (lunar caustic) is a white crystalline salt, used in marking inks, medicine and chemical analysis. How many kilograms of silver nitrate ($AgNO_3$) are there in :

a. 13.0 lb mol $AgNO_3$.
b. 55.0 g mol $AgNO_3$

Solution

a. $$\frac{13.0\ \text{lb mol } AgNO_3}{} \left| \frac{170\ \text{lb } AgNO_3}{1\ \text{lb mol } AgNO_3} \right| \frac{1\ \text{kg}}{2.205\ \text{lb}} = 1002\ \text{kg } \mathbf{or\ 1000\ kg}$$

b. $$\frac{55.0\ \text{g mol } AgNO_3}{} \left| \frac{170\ \text{g } AgNO_3}{1\ \text{g mol } AgNO_3} \right| \frac{1\ \text{kg}}{1000\ \text{g}} = \mathbf{9.35\ kg}$$

Problem 1.3 A

Phosphoric acid is a colorless deliquescent acid used in the manufacture of fertilizers and as a flavoring agent in drinks. For a given 10 wt % phosphoric acid solution of specific gravity 1.10 determine:

a. the mol fraction composition of this mixture.

b. the volume (in gallons) of this solution which would contain 1 g mol H_3PO_4.

Solution

a. Basis: 100 g of 10 wt% solution

	g	MW	g mol	mol fr
H_3PO_4	10	97.97	0.102	0.020
H_2O	90	18.01	5.00	0.980

b. Specific gravity $= \dfrac{\rho_{soln}}{\rho_{ref}}$ The ref. liquid is water

The density of the solution is $\dfrac{1.10\ \text{g soln/cm}^3\ \text{soln}}{1.00\ \text{g H}_2\text{O/cm}^3} \Big| \dfrac{1.00\ \text{g H}_2\text{O/cm}^3}{} = 1.10\ \dfrac{\text{g soln}}{\text{cm}^3}$

$$\frac{1\ \text{cm}^3\ \text{soln}}{1.10\ \text{g soln}} \Big| \frac{1\ \text{g soln}}{0.1\ \text{g H}_3\text{PO}_4} \Big| \frac{97.97\ \text{g H}_3\text{PO}_4}{1\ \text{g mol H}_3\text{PO}_4} \Big| \frac{264.2\ \text{gal}}{10^6\ \text{cm}^3} = \mathbf{0.24\ gal/g\ mol}$$

Problem 1.3 B

The density of a liquid is 1500 kg/m^3 at 20 °C.

a. What is the specific gravity 20°C/4°C of this material.

b. What volume (ft^3) does 140 lb$_m$ of this material occupy at 20°C.

Solution

Assume the reference substance is water which has a density of 1000 kg/m^3 at 4°C.

a. Specific gravity $= \dfrac{\rho_{soln}}{\rho_{ref}} = \dfrac{(\text{kg/m}^3)\text{soln}}{(\text{kg/m}^3)\text{ref}} = \dfrac{1500\ \text{kg/m}^3}{1000\ \text{kg/m}^3} = \mathbf{1.50}$

b. $$\frac{1\ \text{m}^3\ \text{liquid}}{1500\ \text{kg}} \Big| \frac{1\ \text{kg}}{2.20\ \text{lb}} \Big| \frac{35.31\ \text{ft}^3}{1\ \text{m}^3} \Big| \frac{140\ \text{lb}_m}{} = \mathbf{1.50\ ft^3}$$

Problem 1.5 A

Complete the table below with the proper equivalent temperatures.

°C	°F	K	°R
- 40.0	----------	------------	-----------
----------	77.0	------------	-----------
----------	----------	698	-----------
----------	----------	------------	69.8

Solution

The conversion relations to use are:

$$°F = 1.8\ °C + 32$$
$$K = °C + 273$$
$$°R = °F + 460$$
$$°R = 1.8\ K$$

°C	°F	K	°R
- 40.0	**- 40.0**	**233**	**420**
25.0	77.0	**298**	**437**
425	**797**	698	**1257**
- 235	**-390**	**38.4**	69.8

Problem 1.5 B

The specific heat capacity of toluene is given by following equation

$$C_p = 20.869 + 5.293 \times 10^{-2}\, T$$

where C_p is in Btu/(LB mol) (° F) and T is in ° F

Express the equation in cal/(g mol) (K) with T in K.

Solution

First, conversion of the units for the overall equation is required.

$$C_p = \frac{[20.869 + 5.293 \times 10^{-2}\,(T_{°F})]\ \text{Btu}}{1\ (\text{lb mol})\ (°F)} \left| \frac{252\ \text{cal}}{1\ \text{Btu}} \right| \frac{1\ \text{lb mol}}{454\ \text{g mol}} \left| \frac{1.8\ °F}{1\ K} \right.$$

$$= [\,20.869 + 5.293 \times 10^{-2}\,(T_{°F})]\,\frac{\text{cal}}{(\text{g mol})\ (K)}$$

Note that the coefficients of the equation remain unchanged in the new units for this particular conversion. The T of the equation is still in °F, and must be converted to kelvin.

Heat and Temperature

There are many different forms of energy like heat, light, sound, electrical, kinetic, potential. All of these forms of energy have the ability to do work. One form of energy may be transformed into another. For example; potential (stored chemical) energy is converted to heat energy during combustion. Kinetic energy (as a result of friction) and electrical energy may also be converted to heat.

Heat :- Is a measure of the total kinetic energy of the atoms or molecules in a body.

Temperature :- Is a measurement of the average kinetic energy of the molecules in an object or system and can be measured with a thermometer or a calorimeter. It is a means of determining the internal energy contained within the system. The units of heat is measured in Joules (J), kilo Joules (kJ), Btu.

The heat content of a body will depend on its temperature, its mass, and the nature of material. Heat energy is always transferred from an object at high temperature to one at lower temperature. Temperature is not the same as heat. Temperature measures the degree of hotness of a body. It doesn't depend on the mass or the material of an object. It can be thought of as a measure of the average kinetic energy of the atoms or molecules in a body. Temperature is measured using a variety of temperature scales. **The most commonly used are described in the following :-**

1. **The Celsius Scale (°C)** :- This scale puts the freezing point of water at 0 ºC and the boiling point of water at 100 ºC. The temperatures in between are divided up into 100 units (degrees).
2. **The Kelvin Scale (°K)** :- This scale has absolute zero as the zero point on it's scale. The size of the degree is the same as a Celsius degree. There are no negative temperatures in this scale and absolute zero is 273 degrees below 0 °C.
3. **Fahrenheit scale (°F)** :- Is a scale based on 32 for the freezing point of water and 212 for the boiling point of water, the interval between the two being divided into 180 parts.
4. **Rankine scale (°R)** :- Absolute zero, or 0 °R, is the temperature at which molecular energy is a minimum, and it corresponds to a temperature of -459.67°F.

There are many different types of thermometer used for measuring temperature e.g. mercury, alcohol, bi-metallic strip, thermocouple, electrical resistance, brightness thermometer etc.

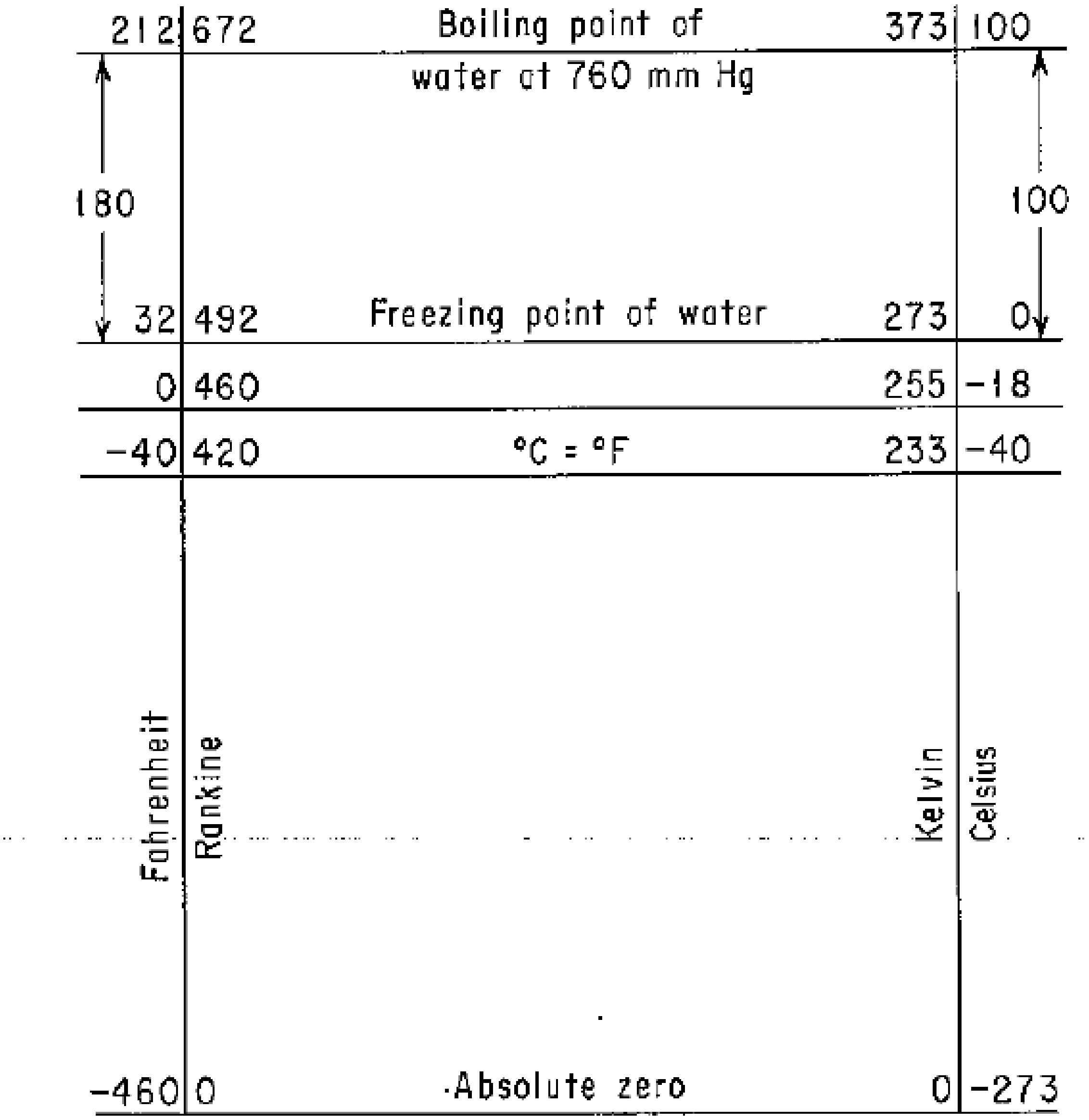


Figure 1 :- Temperature Scales

$$\frac{\Delta °C}{\Delta °F} = 1.8 \quad \text{or} \quad \Delta °C = 1.8 \Delta °F$$

$$\frac{\Delta K}{\Delta °R} = 1.8 \quad \text{or} \quad \Delta K = 1.8 \Delta °R$$

EXAMPLE Temperature Conversion

Convert 100°C to (a) K, (b) °F, and (c) °R.

Solution

(a)
$$(100 + 273)°\text{C}\frac{1\ \Delta\text{K}}{1\ \Delta°\text{C}} = 373\ \text{K}$$

or with suppression of the Δ symbol,

$$(100 + 273)°\text{C}\frac{1\ \text{K}}{1°\text{C}} = 373\ \text{K}$$

(b)
$$(100°\text{C})\frac{1.8°\text{F}}{1°\text{C}} + 32°\text{F} = 212°\text{F}$$

(c)
$$(212 + 460)°\text{F}\frac{1°\text{R}}{1°\text{F}} = 672°\text{R}$$

or

$$(373\text{K})\frac{1.8°\text{R}}{1\ \text{K}} = 672°\text{R}$$

EXAMPLE Temperature Conversion

The thermal conductivity of aluminum at 32°F is 117 Btu/(hr)(ft^2)(°F/ft). Find the equivalent value at 0°C in terms of Btu/(hr)(ft^2)(K/ft).

Solution

Since 32°F is identical to 0°C, the value is already at the proper temperature. The "°F" in the denominator of the thermal conductivity actually stands for Δ°F, so that the equivalent value is

$$\frac{117\ (\text{Btu})(\text{ft})}{(\text{hr})(\text{ft}^2)(\Delta°\text{F})}\left|\frac{1.8\ \Delta°\text{F}}{1\ \Delta°\text{C}}\right|\frac{1\ \Delta°\text{C}}{1\ \Delta\text{K}} = 211\ (\text{Btu})/(\text{hr})(\text{ft}^2)(\text{K/ft})$$

or with the Δ symbol suppressed,

$$\frac{117\ (\text{Btu})(\text{ft})}{(\text{hr})(\text{ft}^2)(°\text{F})}\left|\frac{1.8°\text{F}}{1°\text{C}}\right|\frac{1°\text{C}}{1\ \text{K}} = 211\ (\text{Btu})/(\text{hr})(\text{ft}^2)(\text{K/ft})$$

Pressure can be defined as the measure of force per unit area. The standard SI unit for pressure measurement is the Pascal (Pa) which is equivalent to one Newton per square meter (N/m^2) or the Kilo Pascal (kPa) where 1 kPa = 1000 Pa. In the English system, pressure is usually expressed in pounds per square inch (psi). Pressure can be expressed in many different units including in terms of a height of a column of liquid.

Pressure measurements can be divided into three different categories :-

1. **Absolute pressure** :- It is the pressure referred to zero pressure under complete vacuum.
2. **Degree vacuum** :- It is quantity of pressure below the atmospheric pressure.
3. **Gauge pressure** is the measurement of the difference between the absolute pressure and the local atmospheric pressure. The U.S. standard atmospheric pressure at sea level and 59°F (20°C) is 14.696 pounds per square inchabsolute (psia) or 101.325 kPa absolute (abs).

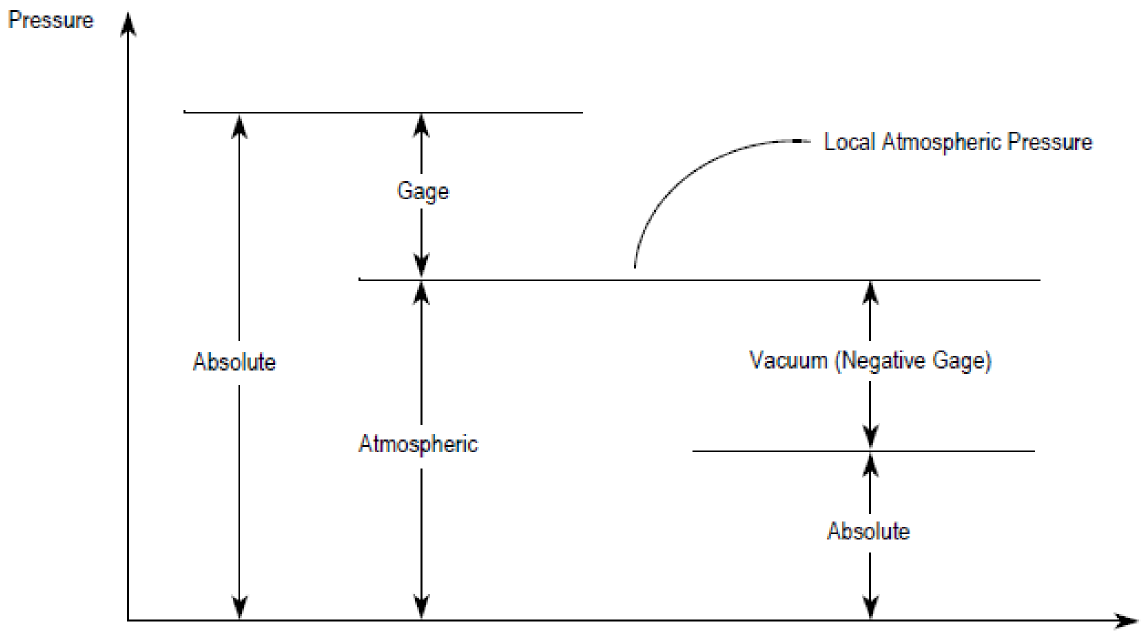


Figure 2 : Pressure Terms Relationship

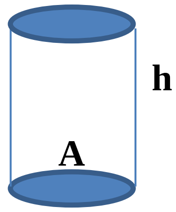
Absolute pressure = Gauge pressure + Atmospheric pressure

Degree Vacuum = Atmospheric pressure – Absolute pressure

Hydrostatic Pressure

Hydrostatic Pressure :- Is the pressure at the base of fluid column, hydrostatic pressure is also called head of fluid it can be calculated as follow :-

$$P = \frac{F}{A} = \frac{m\,g}{A} = \frac{\rho\,V\,g}{A} = \frac{\rho\,\cancel{A}\,h\,g}{\cancel{A}} = \rho\,g\,h$$



Pressure Measuring Devices

Atmospheric pressure is usually measured by a barometer hence this pressure called as the barometric pressure,

At sea-level standard, with pa = 101,350 Pa and ρ g=133,100 N/m^3 , the barometric height is h = 101,350/133,100 = 0.761 m or 761 mm.

Mercury is used because it is the heaviest common liquid. A water barometer would be 34 ft high.

Several devices are used for the measurement of fluid pressure these devices are classified into two types :-

1. **Mechanical Gauge :- The most common type of this class is a Bourdon gauge which normally measure fluid pressure from nearly perfect vacuum to about 7000 atm. The pressure sensing device is a thin metal tube.**

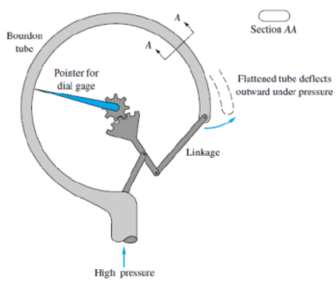


Figure 3 :- Bourdon gauge

2. **Manometers** :- In general, pressure below 3 atm can be measured by manometer. A manometer is a U-shaped tube partially filled with a liquid of known density. Manometers are of three types :-

- **Open end manometer which is used to measure the gauge pressure or degree vacuum. Mercury (Hg) is commonly used as a manometer fluid due to its higher density. The following relation can be used to complete the pressure in (mmHg) if other fluid is used:-**

$$\rho_m h_m = \rho_{Hg} h_{Hg}$$

where :- ρ_m and h_m are the density and height of the fluid manometer.

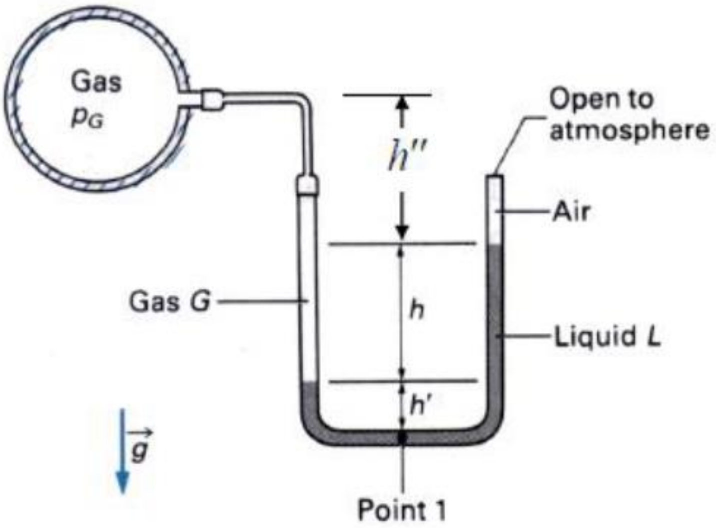


Figure 4 :- Open End Manometer

- **Closed end manometer which is used to measure the absolute pressure.**

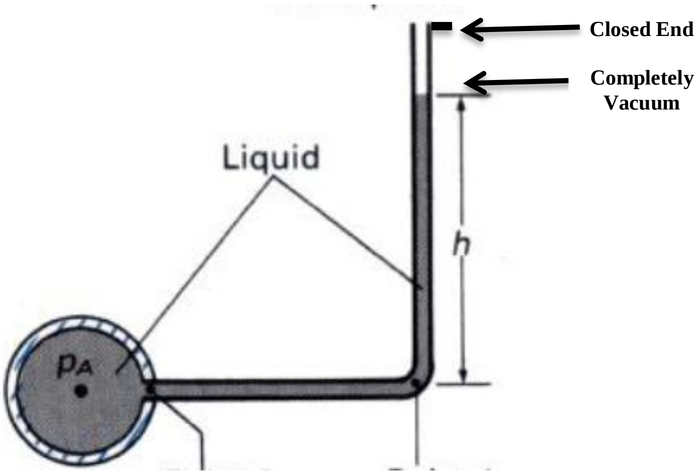


Figure 5 :- Closed End Manometer

- **Differential manometer which is used to measure the difference of pressure between two points in a process line. The general differential manometer equation is :-**

  $P_1 - P_2 = (\rho_m - \rho)g\, h/g_c$

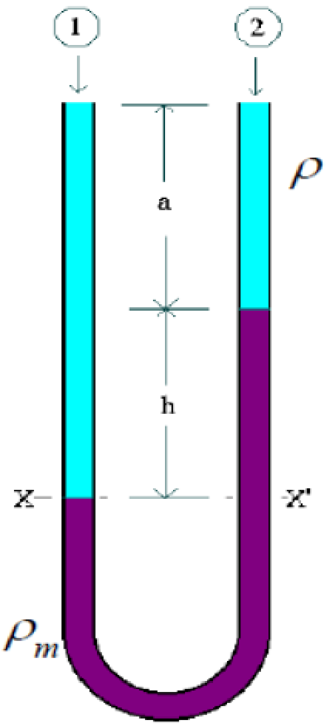


Figure 5 :- Differential Manometer

Example :-

The pressure gauge on the steam condenser reads 26.2 in Hg of vacuum. The barometer reading is 30.4 in Hg. Calculate the pressure in the condenser in psig.

Answer :-

Abs. press. = atm press – degree vacuum

= 30.4 – 26.2 = 4.2 in Hg * (14.7 psi / 29.92 in Hg)

= 2.06

Example :-

Convert the pressure of 340 mm Hg to :-

(a) in H_2O.

(b) kPa .

(c) psi.

Answer :-

(a) P = 340 mm Hg * (34 ft H_2O/760 mm Hg) * (12 in/1 ft) = 182.5 in H_2O

(b) P = 340 mm Hg * (101.3 kPa / 760 mm Hg) = 45.3 kPa

(c) P = 340 mm Hg * (14.7 psi / 760 mm Hg) = 6.58 psi

Example :-

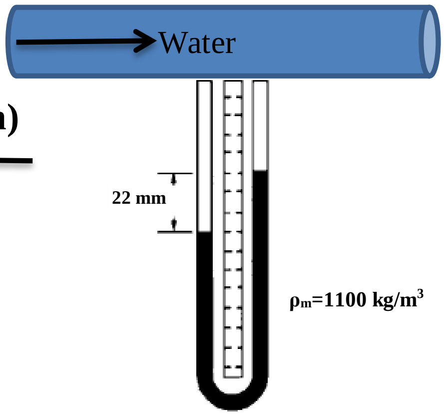
Calculate the pressure drop ($P_1 - P_2$) in Pa measured by the differential manometer show in figure 6 if the density of manometer fluid is 1100 kg/m^3 and h = 22 mm.

Answer :-

$$P_1 - P_2 = [(\rho_m - \rho_{water})\, g\, h]/g_c$$

$$= \frac{(9.81\ m/sec^2)(1100 - 1000\ kg/m^3)(22\ mm)(1m/1000mm)}{1\ (kg\ .\ m)/\ N.\ sec^2}$$

=21.6 Pa



Basis of Calculations

It is necessary to choice and state a basis of calculations as the starting point of solutions of any problem. The following points must be considered in choosing the suitable basis :-

- **The basis must be fitted the available data for example if weight fractions are known choose a total number of moles.**
- **It is usually most convenient to choose the stream that contains most of substances involve in the process or the stream about which most information are known (i.e composition, flow rates, ….. etc.)**
- **The amount of material chosen as the basis must be not very small or very large numbers. A convenient basis is often 1 or 100 since the weight or mole fraction and percent automatically equal the masses or moles of the constituent respectively.**
- **A suitable unit time (i.e hr, day, year, ………etc.) must be selected as the basis for continues process.**
- **The problem of known quantity can be solved with the basis of other suitable quantity according to the above considerations and the results of**

calculations can be converted at the end of solution to the quantity given in the problem.

Example :-

A compound with molecular weight Mwt=119 composed of :-

70.6 wt% C

11.8 wt% N

13.4 wt% O

4.2 wt% H

What is the chemical formula of such compounds ?

Answer :-

Basis = 1 gm mole of compound

Weight of compound = Number of moles of compound * Mwt of compound

= 1 gm mol * 119 gm/gm mol = 119 gm

Weight of C = Weight of compound * Weight Fraction

= 119 * (0.706) = 84 gm

Weight of N = 119 * (0.118) = 14 gm

Weight of H = 119 * (0.042) = 5 gm

Weight of O = 119 * (0.134) = 16 gm

Total weight = 119 gm

Number of moles of C = Wt/Mwt = 84/12 = 7 gm mol

Number of moles of N = 14/14 = 1 gm mol

Number of moles of H = 5/1 = 5 gm mol

Number of moles of O = 16/16 = 1 gm mol

Chemical formula C_7H_5NO

Example :-

A solution of caustic soda in water contains 20 wt% NaOH with specific gravity of 1.196. calculate :-

1. Molarity.
2. Normality.
3. Molality.
4. Mol%.
5. Average molecular weight of solution.

Solution :-

Basis = 100 gm of solution

Weight of NaOH = 100(20/100)= 20 gm

Number of moles of NaOH = wt/Mwt = 20/40 = 0.5 gmmol

Weight of water = 100(80/100) = 80 gm

Number of moles of water = wt/Mwt = 80/18 = 4.44 gmmol

$\rho_{solution}$ = spg * ρ_{water} = 1.196 * 1 gm/cm^3 = 1.196 gm/cm^3

volume of solution = weight / $\rho_{solution}$ = 100/1.196 = 83.6 cm^3 = 0.0836 liter

1. Molarity = number of moles of NaOH/ volume of solution

   = 0.5 gm mol/ 0.0836 liter = 5.98 M

2. Normality = Molarity * valency = 5.98 * 1 = 5.98 N
3. Molality = 0.5 gm mol of NaOH / 0.08 kg water = 6.25 Molal
4. Total moles = number moles of NaOH + number moles of water

   = 0.5 + 4.44 = 4.94 gm mol

   mol % NaOH = (0.5/4.94)*100 = 10.1 %

   mol % H_2O = (4.44/4.94) * 100 = 89.9 %

5. Mwt_{mix} = (Total weight / Total moles) = 100/4.94 = 20.2 gm/gm mol

   OR Mwt_{mix} = 40(10.1/100) + 18(89.9/100) = 4 + 16.2 = 20.2 gm/gm mol

Chemical Equation and Stoichiometry

Stoichiometry :- Is the subjects deals with the combining quantities of the elements or compounds involved in any chemical reaction. Chemical reaction can be generally expressed by the chemical equation which must be balanced i.e the number of atoms of each element must be the same in the both sides of the equation. Such equation provides qualitative and quantitative information essential for stoichiometric calculation.

Stoichiometric coefficients are the numbers that precede the compounds in the chemical equation such coefficients represent the quantity of any reactant theoretically required for complete conversion of other reactants.

Stoichiometric ratio is the ratio between the stoichiometric coefficients in the balanced chemical equation.

The reactants involved in industrial processes are rarely input to the reactor in stoichiometric ratios due to the economic considerations. The following definition must be understood from such point of view.

Limiting reaction :- is the reactant that present in the smallest stoichiometric quantity.

Excess reaction :- is the reactant that present in excess amount over the stoichiometric requirement equivalent to the limiting reaction.

Percentage excess :- is the true excess expressed as a percentage of the amount theoretically required to react completely with the limiting reaction according to the chemical equation.

$$\%\, excess = \frac{excess\ quantity}{theoretical\ quantity\ required}\ x\ 100$$

$$= \frac{in\ put\ quantity - theoretical\ quantity\ required}{theoretical\ quantity\ required}\ x\ 100$$

Conversion is the percent or fraction of some reactant materials that is actually converted into products.

$$\%\, conversion = \frac{quantity\ of\ the\ substance\ that\ reacts}{quntity\ of\ the\ substance\ input\ to\ the\ reactor}\ x\ 100$$

Degree completion of reaction :- is the percentage or fraction of the limiting reactant that is actually converted into products.

$$fraction\ degree\ of\ completion = \frac{quantity\ of\ the\ limiting\ reactant\ that\ reacts}{quantity\ of\ the\ limiting\ reactant\ input\ to\ the\ reactor}$$

Selectivity :- is the ratio of the moles of the desired product to the moles of the undesired product formed in the same reaction, or it can be expressed as the percentage between the quantity of the limiting reactant that is converted to the desired product to the total quantity of the limiting reactant that is converted.

$$\%\, selectivity = \frac{number\ of\ moles\ of\ desired\ product}{number\ of\ moles\ of\ undesired\ product}$$

Yield :- is the ratio between the quantity (mass or moles) of a specified final product to that specified initial product reactant either fed or consumed.

$$yield = \frac{quantity\ of\ final\ product}{quantity\ of\ intial\ product}$$

Example :-

Sodium hypochlorite is manufacture by the following reaction :-

	Cl_2	+	2NaOH	→	NaCl	+	NaOCl	+ H_2O
Mwt	71		40		58.5		74.5	18

710 lb of chlorine gas is bubbled through 2500 lb of sodium hydroxide solution (heavier than water) contains 40 wt% NaOH. The reaction goes to 80% completion . Calculate :-

1. **The limiting reactant, excess reactant and % excess.**
2. **% conversion of the excess reactant.**

Solution :-

1. Number of moles of Cl_2 input = 710/71 = 10 lb mole

Mass of NaOH input = 2500 (40/100) = 1000 lb

Number of moles of NaOH input = (1000/40) = 25 lb mole

Cl_2 is the limiting reactant

NaOH is the excess reactant

% excess = (25 – 20)/20 = 25%

2. % conversion of NaOH = (NaOH reacted / NaOH input) *100

Degree of completion = Cl_2 react / Cl_2 input

80% = Cl_2 react / 10

Cl_2 react = 0.8 * 10 = 8 lbmol

NaOH reacted = 2 * 8 = 16 lb mol

% conversion of NaOH = (16 / 25) * 100 = 64 %

Example :-

$$Al_2O_3 + 3H_2SO_4 \longrightarrow Al_2(SO_4)_3 + 3H_2O$$

Mwt 102 98.1 342 18

Feed in 1080 lb of bauxite are contains 55.4 wt% Al_2O_3 and 2510 lb of sulfuric acid 77.7 wt% H_2SO_4 product 1798 lb of $Al_2(SO_4)_3$

1. **Choice a suitable basis of calculations.**
2. **Identify the limiting reactant, the excess reactant and % excess.**
3. **Fraction degree of completion.**
4. **% conversion of the excess reactant.**
5. **Yield.**
6. **Mass of completion of the reactant and production.**

Solution :-

1. **Basis 1 batch**
2. **Mass of Al_2O_3 input= 1080*(55.4/100) = 598.3 lb**

   Number of moles of Al_2O_3 input = (598.3/102) = 5.87 lb mole

   Mass of H_2SO_4 input = 2510 *(77.7/100) = 1950.3 lb

   Number of moles of H_2SO_4 input = 1950.3/98.1 = 19.88 lb mole

Assume \ Al_2O_3 is the limiting reactant

∴ Theoretical H_2SO_4 required = 3 * 5.87 = 17.61 lb mole

Since H_2SO_4 input = 19.88 lb mole > theoretical (17.61 lb mol)

Right assumption ∴ H_2SO_4 excess reactant

$$\%\ excess = \frac{in\ put\ quantity - theoretical\ quantity\ required}{theoretical\ quantity\ required}\ x\ 100$$

$$= \frac{19.88 - 17.61}{17.61} \times 100 = 12.9\ \%$$

3. $fraction\ degree\ of\ completion = \frac{quantity\ of\ the\ limiting\ reactant\ that\ reacts}{quantity\ of\ the\ limiting\ reactant\ input\ to\ the\ reactor}$

From chemical reaction equation

Number of moles limiting reactant (Al_2O_3) = number of moles of $Al_2(SO_4)_3$ produce

Number of moles of $Al_2(SO_4)_3$ produce = 1798 / 342 = 5.26 lb mole

Fraction of degree of completion = 5.26 / 5.87 = 0.896

4. $\% \; conversion \; of \; H_2SO_4 = \dfrac{quantity \; of \; the \; substance \; that \; reacts}{quntity \; of \; the \; substance \; input \; to \; the \; reactor} \; x \; 100$

$= \dfrac{3 \times 5.26}{19.88} = 79.4 \; \%$

5. $yield = \dfrac{quantity \; of \; final \; product}{quantity \; of \; intial \; product}$

$= \dfrac{1798 \; lb \; of \; Al_2(SO_4)_2}{1080 \; lb \; Beuxite} = \dfrac{1.66 \; lb \; Al_2(SO_4)_2}{1 \; lb \; Beuxite}$

Mass of input

Mass of Al_2O_3 = 1080 lb * (55.4 / 100) = 598.32 lb

Mass of impurities = 1080 lb * (44.6 / 100) = 481.68 lb

Mass of H_2SO_4 = 2510 lb * (77.7 / 100) = 1950.27 lb

Mass of H_2O = 2510 lb * (22.3 / 100) = 559.73 lb

Mass of output

Mass of $Al_2(SO_4)_3$ = 1798 lb

Total mass of water = mass of water produced + mass of water input

= 3*5.26 (18.1) + 559.73 = 845.35 lb

Mass of Al_2O_3 unreacted= (number of moles input – number of moles reacted)*Mwt

= (5.87 – 5.26) * 102 = 62.2 lb

Mass of H_2SO_2 unreacted = (19.88 – 15.78) * 98.1 = 402.21 lb

Mass of impurities = 1080 lb * (44.6 / 100) = 481.68 lb

Total mass output = 3589.44 lb

wt% of $Al_2(SO_4)_3$ = 1798 / 3589.44)= 50.1 %

wt% of water = 845.35 / 3589.44 = 23.55 %

wt% of Al_2O_3 unreacted = 62.2 / 3589.44 = 1.73 %

wt% of H_2SO_2 unreacted = 402.21 / 3589.44 = 11.2 %

wt% of impurities = 481.68 / 3589.44 = 13.42 %