One

Dimensions and Units

1.1 INTRODUCTION

Physical theories gain their definiteness from the mathematical form in which they are expressed. The function of numbering and measuring is indispensable even in order to reproduce the raw material of facts that are to be reproduced and unified in a theory.

DR E.A. CASSIRER[1]
German Philosopher

No better introduction can be given than the above quotes of Dr Cassirer which clearly indicate that a thorough knowledge of dimensions and the various systems of units is not only essential but a must for a logical understanding of the subject. Mathematics and technology are international languages. Engineers converse effectively in formulae and units. To understand one another, communication is required in commonly accepted units. The expression of results of measurements and/or of calculations in a symbolic and numerical form is essential for the development of physics, chemistry and technology. The study of stoichiometry is no different than that of the other sciences and one must start with the understanding of fundamental quantities, namely, dimensions. This will facilitate appropriate and consistent units in solving stoichiometric problems. This chapter not only deals with these fundamentals but also with the methods of conversion of the units from one system to another.

1.2 DIMENSIONS AND SYSTEMS OF UNITS

According to Maxwell, every physical quantity can be expressed as a product of a pure number and an unit, where the unit is a selected reference quantity in terms of which all quantities of the same kind can be expressed. Physical entities are defined by means of certain quantities, such as mass, length, pressure, energy, etc. While defining a particular physical quantity, two questions need to be answered: (i) What would be the most convenient unit? (ii) What would be the best form and material for the standard physically representing that unit? Physical quantities can be classified as *fundamental* quantities and *derived* quantities. The first group consists of four quantities, namely length, mass, time and temperature. These are called *dimensions* or *base units* and are represented by symbols L, M, θ and T. The second group consists of quantities derived from the fundamental quantities, such as area, force, pressure, energy etc. It follows, therefore, that *derived* quantities are represented algebraically in terms of multiplication and division.

The fundamental quantities are represented by a system of units according to the system of measurement. Basically the *standard* physically representing the base unit differs in different systems of units. In this chapter four systems of units, viz. fps, mks, cgs and SI will be discussed.

The fps system, developed in England, is based on foot, pound and second as standard measurements for length, mass and time respectively. This is commonly known as US Customary Units system.

In 1791, in France, a system of units entirely based on unit of length, the *metre* was created. Because of its foundation entirely based on the metre, this system got the name *Système Metrique* or Metric System (mks). The unit of mass in the metric system is kilogram. An important feature of the system was the decimal expression. This system was increasingly adopted in various countries, including India. In India, the mks system was introduced in 1957. In second half of the nineteenth century (around 1860), the British Association for the Advancement of Science (BAAS) played an important role in developing the cgs system in which three base units were chosen, namely, the centimetre, gram and second. It is needless to say that this cgs system is derived from the mks system as the base standards of the cgs system were accepted to be those of the mks system. In practice, it is difficult to work with the mks system alone, and therefore, these two systems were used side by side, depending on the convenience. For example, it was common to express the density in g/cm^3 rather than in kg/m^3 (or kg/l) in mks system.

For better international understanding, in particular, in science and technology and in international and trade relations, a need for an international system of units was felt. At the 10th General Conference on Weights and Measures in 1954 at Paris, it was decided to have an international practical system of units, based on six base units, namely, metre, kilogram, second, ampere, kelvin and candela. It may be seen that first four base units are the same as those in the mks system. In 1960, the 11th General Conference on Weights and Measures in Paris gave the name *Le Système International d'Unitès* or the International System of Units and abbreviated as SI in all languages. Along with six base units, two more supplementary units, *radian* and *steradian* were also defined.

Later it became evident that the quantity mass, although it may be an appropriate concept in mechanics, is entirely unsuitable for use in chemistry where the molecular structure and in particular, the number of molecules in a system is much more relevant than its total mass. For this reason, the concept *amount of substance* was introduced as a base unit by the 14th General Conference on Weights and Measures in 1971 which by definition is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12 and this unit of quantity was called a *mole* (abbreviated as mol). The unified scale of mole thus obtained gives value of the relative atomic mass. Reference 2 gives most important aspects of basic meteorology. Reference 3, 4 and 5 gives an excellent account of SI. India adopted SI units through the Standards of Weights and Measures Act, 1976.

1.3 FUNDAMENTAL QUANTITIES

The fundamental quantities in different systems of units are given in Table 1.1.

Table 1.1 Fundamental Quantities[3]

Fundamental Quantity	System of Units			Symbolic Abbreviation			Dimension
	SI	Metric	fps	SI	Metric	fps	
Length	Metre	Metre	Foot	m	m	ft	L
Mass	Kilogram	Kilogram	Pound	kg	kg	lb	M
Temperature	Kelvin	Celsius	Fahrenheit	K	°C	°F	T
Time	Second	Second	Second	s	s	s	θ
Electric current	Ampere	Ampere	Ampere	A	A	A	I
Amount of substance	Mole	—	—	mol	—	—	n
Luminous intensity	Candela	—	—	cd	—	—	

The thermodynamic temperature (kelvin), defined in SI, is accepted as the absolute temperature in the metric system. The thermodynamic temperature scale is defined by choosing the triple point of water as the fundamental fixed point, and assigning to it the temperature value of 273.16 degrees kelvin, exactly. In other words, kelvin, the unit of thermodynamic temperature, is 1/273.16 of the thermodynamic temperature of the triple point of water. In the fps system, the absolute temperature is Rankine.

$$\text{Degree Kelvin (K)} \quad = {}^\circ\text{C} + 273.15^*$$

$$\text{Degree Rankine (}^\circ\text{R)} \quad = {}^\circ\text{F} + 459.67$$

The abbreviation "deg" will be used in this book to express an interval (or difference) of temperatures in Celsius or Fahrenheit to distinguish it from the temperature values.

$$60^\circ\text{C} - 30^\circ\text{C} = 30 \text{ deg C}$$

$$120^\circ\text{F} - 85^\circ\text{F} = 35 \text{ deg F}$$

$$1 \text{ deg F} = 1.8 \text{ deg C}$$

*The thermodynamic temperature **213.15** K is by definition **0.01** K below the thermodynamic temperature of the triple point of water. In the examples in the text, SI and metric units are given. While giving a conversion of K to °C or vice versa, the difference of 0.15 will be ignored for the practical purpose.

For expressing the temperature interval in absolute temperature scale, the same symbol is used.

$$280\ \text{K} - 235\ \text{K} = 45\ \text{K}$$

$$520\ {}^{\circ}\text{R} - 480\ {}^{\circ}\text{R} = 40\ {}^{\circ}\text{R}$$

$$30\ \text{deg C} = 30\ \text{K}$$

$$35\ \text{deg F} = 35\ {}^{\circ}\text{R}$$

The supplementary SI units, radian and steradian, are not discussed as these are not used in the book. Although, the International Organization for Standardization (ISO) have recommended comma (,) as a decimal marker, the current practice of using a point (.) as the decimal marker in India will be followed in this book.

1.4 DERIVED QUANTITIES

There can be any number of derived quantities, and hence, it is difficult to list all of them. However, the commonly used quantities for stoichiometric calculations in SI, mks and cgs systems are listed in Table 1.2. The International Committee for Weights and Measures have considered that in general, cgs units should preferably not be used with SI. Considering the increasing adoption of SI in a large number of countries and also in India (particularly in science and technology), the SI will be followed in this book.

Table 1.2 Derived Quantities[3]

Derived Quantity	Units in SI/mks/cgs System	Abbreviated Units	Symbol	Dimension
Area	Square metres	m^2	A(S)	L
	Square centimetres	cm^2		L
Volume	Cubic metres	m^3	V(v)	L^3
	Cubic centimetres	cm^3		L^3
	Cubic decimetres	dm^3		L^3
Capacity	Litres	l	V	L^3
Linear velocity	Metres per second	m/s	u, v, v	$L\ \theta^{-1}$
Linear acceleration	Metres per second per second	m/s^2	a, g	$L\ \theta^{-2}$
Density	Kilograms per cubic metre	kg/m^3	ρ	$M\ L^{-3}$
	Grams per millilitre	g/ml		$M\ L^{-3}$
Specific volume	Cubic metres per kilogram	m^3/kg	v	$L^3\ M^{-1}$
Force	Newtons	N	F	$M\ L\ \theta^{-2}$
	kilograms-force* (kilopounds)	kgf (kp)		F

* base unit in mks system

Table 1.2 (Contd.)

Derived Quantity	Units in SI/mks/cgs System	Abbreviated Units	Symbol	Dimension
Force	Dynes	dyn		$M\,L\,\theta^{-2}$
Pressures	Newtons per square metre (Pascals)	N/m^2 (Pa)	P	$M\,L^{-1}\,\theta^{-2}$
	Kilograms-force or kilopounds per square centimetre	kgf/cm^2 (kp/cm^2)		$F\,L^{-2}$
Work/Energy	Joules	J	Q	$M\,L^2\theta^{-2}$
	Ergs	erg		$M\,L^2\theta^{-2}$
	Metres kilogram force	m.kgf		M F
Heat/Enthalpy	Joules	J	Q, H	$M\,L^2\theta^{-2}$
	Kilocalories	kcal		$M\,L^2\theta^{-2}$
Power	Kilowatts	kW	P	$M\,L^2\theta^{-3}$
	Horsepowers	HP		$M\,F\,\theta^{-1}$
Heat flow	Joules per second	J/s or W	ϕ	$M\,L^2\theta^{-3}$
	Kilocalories per hour	kcal/h		$M\,L^2\theta^{-3}$
Specific/ Absolute humidity	Kilograms water per kilogram dry air	kg/kg	H, x	$M^o\,L^o\,\theta^o$
Relative humidity	Nil	Nil	*RH*	$M^oL^o\theta^o$
Saturation ratio	Nil	Nil	ϕ	$M^o\,L^o\,\theta^o$
Mass flow rate	Kilograms per hour	kg/h	q_m	$M\,\theta^{-1}$
Volumetric flow rate	Cubic metres per hour	m^3/h	q_v	$L^3\,\theta^{-1}$
	Litres per second	l/s		$L^3\,\theta^{-1}$
Heat capacity	Joules per kilogram per degree kelvin	J/(kg.K)	C	$L^2\,T^{-1}$
	Kilocalories per kilogram per degree Celsius	kcal/(kg. deg C)		$L^2\theta^{-2}T^{-1}$
Molar heat capacity	Joules per kilogram mole per degree Kelvin	J/(kmol. K)	c_p	$M\,L^2\theta^{-2}n^{-1}T^{-1}$
	Kilocalories per kilogram mole per degree Celsius	kcal/(kmol. deg C)		$M\,L^2\theta^{-2}n^{-1}T^{-1}$

1.4.1 Force

The definition of force follows from Newton's second law of motion, which states that force is proportional to the product of mass and acceleration.

$$F \propto M \times a \tag{1.1}$$

Introducing a proportionality constant K,

$$F = K\,M\,a \tag{1.2}$$

Force and acceleration are both vector quantities and hence they should act in the same direction. There are two ways of selecting the constant K. In one case, K is selected as unity (dimensionless), and with this value, the units newton (SI) and dyne are defined.

The newton (N) is the force which when applied to a body having a mass of one kilogram gives it an acceleration of one m/s^2.

The dyne (dyn) is the force which when applied to a body having a mass of one gram gives it an acceleration of one cm/s^2.

Based on these definitions,

$$1\text{ N} = 10^5\text{ dyn}$$

A similar unit in the fps system is the poundal which is the force, when applied to a body having a mass of one pound gives it an acceleration of one ft/s^2.

$$1\text{ pdl} = 30.48 \times 453.5924 = 13\,825.5\text{ dyn}$$

Another choice of the constant K yields the technical unit of force. Force is defined here as a fundamental quantity. Thus the constant K becomes a dimensional quantity. Its numerical value if not unity but fixed at $1/g_c$.

$$F = \left(\frac{1}{g_c}\right) M\,a \tag{1.3}$$

$$g_c = 9.806\,65\text{ (kg.m)/(kgf.s}^2\text{)} = 32.174\text{ (lb.ft)/(lbf.s}^2\text{)}$$

g_c is called the Newton's law conversion factor. Its value corresponds to the acceleration due to gravity (g) at the mean sea level (9.806 65 m/s^2 or 32.174 ft/s^2). It should be clearly noted that g_c does not vary eventhough g varies from place to place. In ordinary calculations, however, g/g_c is taken as 1.0 kgf/kg. By definition, g_c has the units of 1 (kg.m)/(N.s^2) in SI.

The technical units of force in mks and fps systems are kilogram-force and pound-force, respectively.

The kilogram-force (kgf) is the force which when applied to a body having a mass of one kilogram gives it an acceleration of 9.806 65 m/s^2. In some continental countries, the name kilopond (kp) is used in place of kilogram force.

The pound force (lbf) is the force which when applied to a body having a mass of one pound gives it an acceleration of 32.174 ft/s^2.

The force becomes weight when the body acts under gravitational acceleration (g), i.e. when $a = g$ in Eq. (1.2).

$$\text{Weight, } G = \left(\frac{1}{g_c}\right) M\,g \tag{1.4}$$

Since g and g_c are assumed equal for all practical purposes.

$$G = M \tag{1.5}$$

Thus the values of weight and mass become practically equal.

In order to differentiate between the terms mass and force, their units are distinguished by writing "f" at the end of the fundamental unit of force.

The measurement of force, pressure, mass and weight have in the past been conveniently made through the use of gravitational acceleration without taking into account the variation of this acceleration from one location to another, which was normally insignificant in the applications. However, as process industries have spread geographically and as the processes involved require more sophisticated control, the difference between the points of calibration and use of an instrument has become more significant. The practice of ignoring the difference was also fundamentally wrong. Both these reasons have necessitated the use of SI in the current practice.

1.4.2 Volume

Volume is measured in cubic metres (SI), in litres (mks) and gallons (fps).

A litre is the volume occupied by a mass of one kilogram of pure air free water at the temperature of its maximum density and under normal atmospheric pressure. The cubic decimetre and litre are unequal and differ by about 28 parts in 10^6 parts. Hence the word "litre" can be employed as a special name of the cubic decimetre. However, the name litre should not be employed to give the results of high accuracy volume measurements.

$$1 \text{ litre} = 1.000\,028 \text{ cubic decimetres} \qquad \text{(accurate)}$$

Approximately, $\quad 1 \text{ cubic metre} = 1000 \text{ litres} = 1 \text{ kilolitre}$

The Imperial and US gallons are different. The former is defined as the volume occupied by a quantity of distilled water, which weighs 10 lb in air at the temperature of 62°F (289.8 K or 16.7°C) and the pressure of 30 in Hg (762 torr). The US gallon is equal to 231 in^3 (3.7854 l).

1.4.3 Pressure

Pressure is defined as the force acting on unit area exposed to the pressure

$$p = \frac{F}{A} \tag{1.6}$$

The common units of pressure in SI, mks and fps units are N/m^2 (known as pascal, symbol Pa), kgf/cm^2 (or kp/cm^2) and lbf/in^2 (commonly known as psi) respectively.

Pressure is normally measured with the help of a gauge which registers the difference between the pressure in vessel and the local atmospheric pressure. This is known as the gauge pressure and the letter "g" follows the unit. The gauge pressure does not indicate the true total pressure. In order to obtain the true pressure or pressure above reference zero, it is necessary to add the local atmospheric or barometric pressure expressed in coherent units to the gauge pressure. This sum is the absolute pressure and the letter "a" follows the units. In general, if no letter follows the pressure units, it is taken as absolute pressure.

$$\text{Absolute pressure} = \text{gauge pressure} + \text{atmospheric pressure} \tag{1.7}$$

Although the actual atmospheric pressure varies from one locality to another, its value at the mean sea level is 101 325 N/m^2 or Pa (1.033 kgf/cm^2) and is called the normal atmosphere. In SI, the standard atmosphere and bar are accepted as the practical units.

$$1 \text{ bar} = 10^5 \text{ Pa} = 1.019\,716 \text{ kgf/cm}^2$$

Quite often, the pressure is expressed in pressure heads.

$$\text{Pressure head} = \text{absolute pressure/density} \tag{1.8}$$

The more commonly used pressure heads are in terms of mercury and water columns.

$$1 \text{ atm} = 760 \text{ torr (or mm Hg)} = 10.33 \text{ m } H_2O$$

Vacuum refers to sub-atmospheric pressure.

$$\text{Absolute pressure} = \text{atmospheric pressure} - \text{vacuum} \tag{1.9}$$

Vacuum is usually expressed in torr (mm Hg).

1.4.4 Work / Energy and Power

Work (energy) is defined as the product of the force acting on a body and the distance travelled by the body.

$$W = F \times L \tag{1.10}$$

The units of work (energy) in SI, mks, cgs and fps systems are joule, m.kgf, erg and ft.lbf respectively.

Energy is a physical entity which is present in a system in different forms, e.g., mechanical (work), electromagnetic, chemical or thermal. One form of energy is convertible to another form.

One joule is the work done when the point of application of one newton force, moves a distance of one metre in the direction of the applied force.

One erg is the work done when the point of application of one dyne force moves a distance of one centimetre in the direction of the applied force.

$$1 \text{ J} = 10^7 \text{ erg}$$

Power P is defined as the work W done per unit time.

$$\text{Power } P = \frac{W}{\theta} \tag{1.11}$$

$$1 \text{ Watt} = 1 \text{ J/s}$$

$$\begin{aligned} 1 \text{ metric horsepower} &= 75 \text{ (m.kgf)/s} = 0.7355 \text{ kW} \\ &= 0.986\,32 \text{ British horsepower} \end{aligned}$$

$$\begin{aligned} 1 \text{ British horsepower} &= 550 \text{ (ft.lbf)/s} = 0.7457 \text{ kW} \\ &= 1.013\,87 \text{ metric horsepowers} \end{aligned}$$

Heat

Heat is one form of energy that flows from higher temperature to lower temperature. The units of heat in SI, mks, cgs and fps systems are the joule (J), kilocalorie (kcal), calorie (cal) and British thermal unit (Btu) respectively.

There are several definitions of Btu and cal. All are defined in terms of the joule. Each Btu and its corresponding cal are related by a heat capacity equation.

$$1 \text{ calorie (thermochemical)} = 4.184 \text{ J}$$

$$1 \text{ calorie (International Steam Tables)} = 4.1868 \text{ J}$$

$$1 \text{ calorie [at 288.15 K (15°C)]} = 4.1855 \text{ J}$$

$$1 \text{ Btu (International Steam Tables)} = 1055.056 \text{ J}$$

In this book, International Steam Tables Btu and cal will be used. The Celsius Heat Unit (CHU) and Therm were also used in the fps system.

$$1 \text{ CHU} = 1.8 \text{ Btu}$$

$$1 \text{ Therm} = 10^5 \text{ Btu}$$

In SI system, heat flux (i.e., heat flow) is customarily expressed in watts (W).

1.4.5 Derived Electrical Units

Current is the fundamental quantity in electricity. The volt V is the unit of electromotive force or of potential difference. Resistance (R in ohms) of the conductor is defined as

$$R = \frac{V}{I} \tag{1.12}$$

where R is the resistance in ohms, V is the potential difference in volts and I is the current in amperes.

Coulomb is the unit of quantity of electricity and is defined as the quantity of electricity carried in one second by a current of one ampere across any cross-section.

$$1 \text{ Faraday (F)} = 96\,485.309 \text{ coulombs/mol} \quad \text{(based on carbon-12)}$$

The quantity coulomb is an important quantity in electrochemistry.

1.5 CONVERSIONS

It is often required to convert units of a particular quantity from one system to another. Table 1.3 gives a brief list of the conversions[5, 6, 7, 8, 9] in common use. Appendix I gives the conversions in a direct usable form.

The precision to which a given conversion factor is known, and its application, determine the number of significant figures which should be used. While comparing the data given in Appendix I with those given in many handbooks and standards, it may be hinted that different sources disagree, in many cases, in the fifth or further figure which indicates that four or five significant figures represent the precision for these factors fairly accurately. At present, the accuracy of process instrumentation, analog or digital, needs only three significant figures. Additional accuracy is only needed in basic fundamental research and can be waste of time in the industrial practice.

Table 1.3 Condensed Table of Conversion Factors

Length:	1 m = 1.093 613 yd
	= 3.280 84 ft
	1 cm = 0.393 701 in
	1 km = 0.621 37 miles
	= 0.539 96 international nautical miles
Area:	1 m^2 = 10.763 91 ft^2
	= 1.195 99 yd^2
	1 cm^2 = 0.155 in^2
	1 km^2 = 0.386 102 $mile^2$
	1 ha = 100 00 m^2
	= 2.471 05 acre
	= 0.003 861 $mile^2$
Volume:	1 m^3 = 1000 dm^3 = 1000 l
	= 35.314 67 ft^3
	= 1.307 95 yd^3
	= 6.2898 barrels (oil)
	1 cm^3 = 0.061 024 in^3
Capacity:	1 l = 0.219 969 Imperial gal
	= 0.264 172 US gal
	= 0.035 3147 ft^3
	1 kl = 1000 l
	= 0.000 810 71 acre.ft
Mass:	1 kg = 1000 g
	= 2.204 623 lb

(Contd.)

Table 1.3 (Contd.)

Mass:	1 t	= 1000 kg
		= 0.984 21 T
		= 1.102 311 T (short, used in USA)
		= 2204.623 lb
	1 g	= 15.4324 grain
Density:	1 kg/dm^3	= 1 kg/l
		= 70 156.8 grain/Imperial gal
		= 58 417.82 grain/US gal
	1 g/cm^3	= 62.427 95 lb/ft^3
		= 10.0224 lb/Imperial gal
		= 8.345 405 lb/US gal
		= 0.036 127 1b./in^3
Specific volume:	1 m^3/kg	= 16.018 48 ft^3/lb
		= 99.7765 Imperial gal/lb
		= 119.8265 US gal/lb
Force:	1 N	= 0.101 972 kgf
		= 0.224 809 lbf
Pressure:	1 kPa	= 0.010 197 kgf/cm^2
		= 0.145 038 lbf/in^2 or psi
	1 bar	= 0.1 MPa
		= 1.019 716 kgf/cm^2
		= 14.503 77 lbf/in^2
	1 atm	= 101.325 kPa (normal sea level)
		= 1.033 227 kgf/cm^2
		= 14.695 95 lbf/in^2
	1 torr (1 mm Hg)	= 133.3224 Pa
		= 0.039 37 in Hg
Energy:	1 J	= 0.238 846 cal (IT)
		= 2.777 778 $\times 10^{-7}$ kWh
		= 9.478 172 $\times 10^{-4}$ Btu (IT)
		= 0.101 972 kgf.m
		= 0.737 562 lbf.ft
		= 9.869 233 $\times 10^{-3}$ l.atm
	1 kWh	= 859.8452 kcal (IT)
		= 3412.142 Btu (IT)
	1 kcal	= 3.968 321 Btu (IT)
	1 kgf.m	= 7.233 lbf.ft
Power:	1 kW	= 1.359 62 metric hp
		= 1.341 02 hp (British)
		= 859.8452 kcal/h

(Contd.)

Table 1.3 (Contd.)

Power:	1 kW = 3412.142 Btu/h
	1 (m.kgf)/s = 7.233 (ft.lbf)/s
Heat capacity:	1 J/kg.k) = $2.388\ 46 \times 10^{-4}$ kcal/(kg.deg C)
	= $2.388\ 46 \times 10^{-4}$ Btu/(lb.deg F)
Temperature:	°C = 5/9 (F° – 32)
	°F = (9/5) °C + 32

1.6 RECOMMENDATIONS FOR USE OF UNITS

The recommendations issued by the General Conference on Weights and Measures, International Organization for the Standardization, Bureau of Indian Standards [IS : 1890 (Part 0)-1983] and American Society for Testing Materials (E – 380)[10] for the use of units are summarised below.

(i) SI prefixes are given in Table 1.4.

Table 1.4 SI Prefixes

Factor	Prefix	Symbol
10^{24}	yotta	Y
10^{21}	zetta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

(ii) An exponent attached to a compound prefix-unit implies that the exponent refers to the entire compound and not just to the base symbol.
1 cm^3 means volume of a cube having one cm side.

(iii) The product of two or more units may be indicated in any one of the following ways.

Correct: N.m, N*m or N m   Incorrect : Nm