Chemical Engineering Principles

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Chapter One
Introduction to Engineering Calculations:

1.1 Units and Dimensions

Dimensions are our basic concepts of measurement such as **length, time, mass, temperature, and so on; units** are the means of expressing the dimensions, such as feet or centimeters for length, and hours or seconds for time.
In this lectures you will use the two most commonly used systems of units:

1. **SI,** formally called Le Systeme Internationale d'Unites, and informally called SI or more often (redundantly)the SI system of units.
2. **AE,** or American Engineering system of units.

Dimensions and their respective units are classified as fundamental or derived:

- **Fundamental** (or basic) dimensions/units are those that can be measured independently and are sufficient to describe essential physical quantities.
- **Derived** dimensions/units are those that can be developed in terms of the fundamental dimensions/units.

Tables 1.1 and 1.2 list both basic, derived, and alternative units in the SI and AE systems. Figure 1.1 illustrates the
relation between the basic dimensions and some of the derived dimensions.

One of the best features of the SI system is that (except for time) units and their multiples and submultiples are related by standard factors designated by the prefix

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indicated in Table 1.3.

Table 1.1 SI Units

Physical Quantity	Name of Unit	Symbol for Unit*	Definition of Unit
	Basic SI Units		
Length	metre, meter	m	
Mass	kilogramme, kilogram	kg	
Time	second	s	
Temperature	kelvin	K	
Molar amount	mole	mol	
	Derived SI Units		
Energy	joule	J	$kg \cdot m^2 \cdot s^{-2} \rightarrow Pa \cdot m^3$
Force	newton	N	$kg \cdot m \cdot s^{-2} \rightarrow J \cdot m^{-1}$
Power	watt	W	$kg \cdot m^2 \cdot s^{-3} \rightarrow J \cdot s^{-1}$
Density	kilogram per cubic meter		$kg \cdot m^{-3}$
Velocity	meter per second		$m \cdot s^{-1}$
Acceleration	meter per second squared		$m \cdot s^{-2}$
Pressure	newton per square meter, pascal		$N \cdot m^{-2}$, Pa
Heat capacity	joule per (kilogram · kelvin)		$J \cdot kg^{-1} \cdot K^{-1}$
	Alternative Units		
Time	minute, hour, day, year	min, h, d, y	
Temperature	degree Celsius	°C	
Volume	litre, liter (dm^3)	L	
Mass	tonne, ton (Mg), gram	t, g	

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Table 1.2 American Engineering (AE) System Units

Physical Quantity	Name of Unit	Symbol
	Some Basic Units	
Length	foot	ft
Mass	pound (mass)	lb_m
Time	second, minute, hour, day	s, min, h (hr), day
Temperature	degree Rankine or degree Fahrenheit	°R or °F
Molar amount	pound mole	lb mol
	Derived Units	
Force	pound (force)	lb_f
Energy	British thermal unit, foot pound (force)	Btu, (ft)(lb_f)
Power	horsepower	hp
Density	pound (mass) per cubic foot	lb_m/ft^3
Velocity	feet per second	ft/s
Acceleration	feet per second squared	ft/s^2
Pressure	pound (force) per square inch	$lb_f/in.^2$, psi
Heat capacity	Btu per pound (mass) per degree F	Btu/(lb_m)(°F)

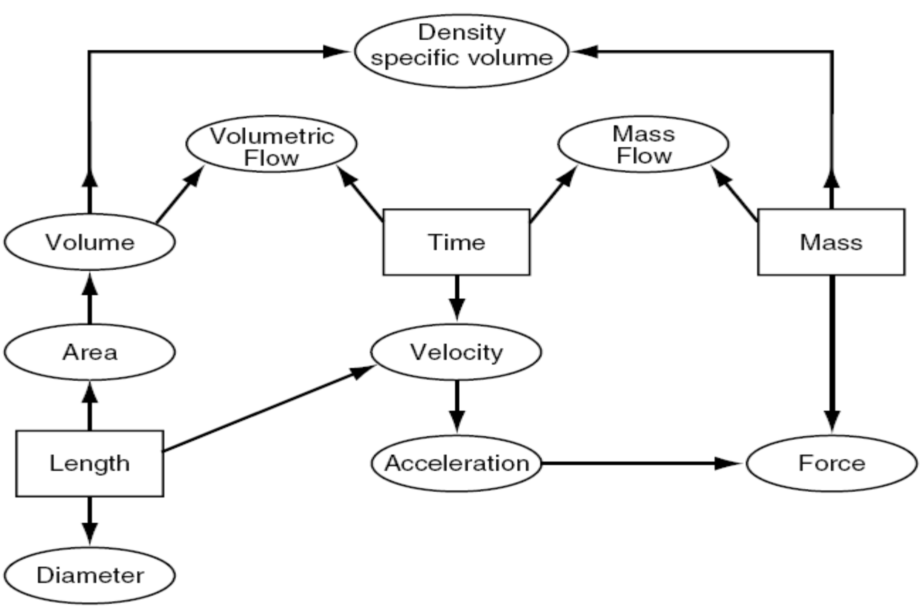

Figure 1.1 Relation between the basic dimensions (in boxes) and various derived dimensions (in ellipses).

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Table 1.3 SI Prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^9	giga	G	10^{-1}	deci	d
10^6	mega	M	10^{-2}	centi	c
10^3	kilo	k	10^{-3}	milli	m
10^2	hecto	h	10^{-6}	micro	μ
10^1	deka	da	10^{-9}	nano	n

Operations with Units

The rules for handling units are essentially quite simple:
Addition, Subtraction, Equality

You can add, subtract, or equate numerical quantities only if the associated units of the quantities are the same. Thus,
the operation

5 kilograms + 3 joules

Cannot be carried out because the units as well as the dimensions of the two terms are different. The numerical
operation

10 pounds + 5 grams

can be performed (because the dimensions are the same, mass) only after the units are transformed to be the same, either pounds, grams, or ounces, or some other mass unit.

Multiplication and Division

You can multiply or divide unlike units at will such as

50(kg)(m)/(s)

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but you cannot cancel or merge units unless they are identical. Thus, 3 m^2/60 cm can be converted to 3 m^2/0.6 m, and then to 5 m, but in m/s^2, the units cannot be cancelled or combined.

Example 1

Add the following:

(a) 1 foot + 3 seconds (b) 1 horsepower + 300 watts

Solution:

The operation indicated by

1 ft + 3 s

has no meaning since the dimensions of the two terms are not the same. In the case of

1 hp + 300 watts

the dimensions are the same (energy per unit time), but the units are different. You must transform the two quantities into like units, such as horsepower or watts, before the addition can be carried out. Since **1 hp = 746 watts,**

746 watts + 300 watts = 1046 watts

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1.1.1 Conversion of Units and Conversion Factors

The procedure for converting one set of units to another is simply to multiply any number and its associated units by ratios termed conversion factors to arrive at the desired answer and its associated units.

If a plane travels at **twice** the speed of sound (assume that the speed of sound is **1100 ft/s),** how fast is it going in **miles per hour**?

We formulate the conversion as follows

$$\frac{2 \times 1100 \text{ ft}}{\text{s}} \left| \frac{1 \text{ mi}}{5280 \text{ ft}} \right| \frac{60 \text{ s}}{1 \text{ min}} \left| \frac{60 \text{ min}}{1 \text{ hr}} \right.$$

$$\frac{\text{ft}}{\text{s}} \qquad \frac{\text{mi}}{\text{s}} \qquad \frac{\text{mi}}{\text{min}}$$

Example 2:

(a) Convert 2 km to miles. (b) Convert 400 in.^{3}/day to cm^3/min.

Solution:

(a) One way to carry out the conversion is to look up a direct conversion factor, namely 1.61 km = 1 mile:

$$\frac{2 \text{ km}}{} \left| \frac{1 \text{ mile}}{1.61 \text{ km}} \right. = 1.24 \text{ mile}$$

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Another way is to use conversion factors you know

$$\frac{2\ \text{km}}{}\left|\frac{10^5\ \text{cm}}{1\ \text{km}}\right|\frac{1\ \text{in.}}{2.54\ \text{cm}}\left|\frac{1\ \text{ft}}{12\ \text{in.}}\right|\frac{1\ \text{mile}}{5280\ \text{ft.}} = 1.24\ \text{mile}$$

$$\text{(b)}\quad \frac{400\ \text{in.}^3}{\text{day}}\left|\left(\frac{2.54\ \text{cm}}{1\ \text{in.}}\right)^3\right|\frac{1\ \text{day}}{24\ \text{hr}}\left|\frac{1\ \text{hr}}{60\ \text{min}}\right. = 4.55\frac{\text{cm}^3}{\text{min}}$$

In part (b) note that not only are the numbers in the conversion of inches to centimeters raised to a power, but the units also are raised to the same power.

Example 3:

An example of a semiconductor is ZnS with a particle diameter of 1.8 nanometers. Convert this value to (a) dm (decimeters) and (b) inches.

Solution:

$$\text{(a)}\quad \frac{1.8\ \text{nm}}{}\left|\frac{10^{-9}\ \text{m}}{1\ \text{nm}}\right|\frac{10\ \text{dm}}{1\ \text{m}} = 1.8 \times 10^{-8}\ \text{dm}$$

$$\text{(b)}\quad \frac{1.8\ \text{nm}}{}\left|\frac{10^{-9}\ \text{m}}{1\ \text{nm}}\right|\frac{39.37\ \text{in.}}{1\ \text{m}} = 7.09 \times 10^{-8}\ \text{in.}$$

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In the AE system the conversion of terms involving pound mass and pound force deserve special attention. Let us start the discussion with Newton's Law:

$$F = Cma \qquad (1.1)$$

Where:

F = force

C = a constant whose numerical value and units depend on those selected for F, m, and a
m = mass

a = acceleration

In the SI system in which the unit of force is defined to be the Newton (N) when **1 kg** is accelerated at **1 m/s^2, a** conversion factor **C = 1 N/(Kg)(m)/s^2** must be introduced to have the force be **1 N:**

$$F = \underbrace{\frac{1\ \text{N}}{\frac{(\text{kg})(\text{m})}{\text{s}^2}}}_{\tilde{C}} \left| \underbrace{\frac{1\ \text{kg}}{}}_{\tilde{m}} \right| \underbrace{\frac{1\ \text{m}}{\text{s}^2}}_{\tilde{a}} = 1\ \text{N} \qquad (1.1)$$

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Because the numerical value associated with the conversion factor is 1, the conversion factor seems simple, even nonexistent, and the units are ordinarily ignored.

In the **AE system** an analogous conversion factor is required. If a mass of 1 1bm is hypothetically accelerated at **g ft/s²**, where **g** is the acceleration that would be caused by gravity (**about 32.2 ft/s²** depending on the location of the mass), we can make the force be 1 1bf by choosing the proper numerical value and units for the conversion factor C:

$$F = \underbrace{\left(\frac{1(\text{lb}_f)(s^2)}{32.174(\text{lb}_m)(\text{ft})}\right)}_{\widetilde{C}}\left(\underbrace{\frac{1\ \text{lb}_m}{}}_{\widetilde{m}}\Bigg|\underbrace{\frac{g\ \text{ft}}{s^2}}_{\widetilde{g}}\right) = 1\ \text{lb}_f \qquad (1.2)$$

The inverse of the conversion factor with the numerical value **32.174** included is given the special symbol $\mathbf{g_c}$

$$g_c = 32.174\frac{(\text{ft})(\text{lb}_m)}{(\text{s}^2)(\text{lb}_f)}$$

But never forget that the pound (**mass**) and pound (**force**) are not the same units in the **AE** system.

Example 4:

What is the potential energy in **(ft)(1b$_f$) of a 100 lb** drum hanging **10 ft** above the surface of the earth with reference to the surface of the earth?

Solution:

Potential energy = P = m g h

Assume that the **100 lb** means **100 lb mass; *g* = acceleration of gravity = 32.2 ft/s^2.**

Figure E1.4 is a sketch of the system.

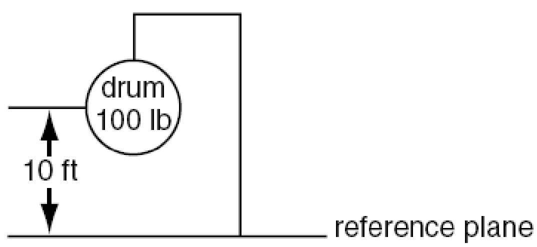

Figure E1.4

$$P = \frac{100\ \text{lb}_m}{} \left| \frac{32.2\ \text{ft}}{\text{s}^2} \right| \frac{10\ \text{ft}}{} \left| \frac{(\text{s}^2)(\text{lb}_f)}{32.174(\text{ft})(\text{lb}_m)} \right. = 1000\ (\text{ft})(\text{lb}_f)$$

Notice that in the ratio of **32.2 ft/s^2** divided by **32.174[(ft)(lbm)]/[(s^2)(lb$_f$)]**, the numerical values are almost equal. Many engineers would solve the problem by saying that **100 lb** × **10 ft = 1000 (ft)(1b)** without realizing that, in effect, they are canceling out the numbers in the **g/g$_c$** ratio, and that the lb in the solution means lb$_f$.

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Example 5:

In biological systems, production rate of glucose is **0.6 μg mol/(mL)(min).** Determine the production rate of glucose for this system in the units of **lb mol/(ft^3)(day).**

Solution:

Basis: 1 min

$$\frac{0.6\ \mu\text{g mol}}{(\text{mL})(\text{min})}\left|\frac{1\ \text{g mol}}{10^6\ \mu\text{g mol}}\right|\frac{1\ \text{lb mol}}{454\ \text{g mol}}\left|\frac{1000\ \text{mL}}{1\ \text{L}}\right|\frac{1\ \text{L}}{3.531\times 10^{-2}\ \text{ft}^3}\left|\frac{60\ \text{min}}{\text{hr}}\right|\frac{24\ \text{hr}}{\text{day}}$$

$$= 0.0539\frac{\text{lb mol}}{(\text{ft}^3)(\text{day})}$$

1.4 Dimensional Consistency (Homogeneity)

The concept of dimensional consistency can be illustrated by an equation that represents the pressure/volume/temperature behavior of a gas, and is known as van der Waals's equation.

$$\left(p + \frac{a}{V^2}\right)(V - b) = RT$$

Inspection of the equation shows that the constant **a** must have the units of **[(pressure)(volume)^2]** for the expression in the first set of parentheses to be consistent throughout.

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If the units of pressure are **atm** and those of volume are **cm³**, a will have the units of **[(atm)(cm)⁶]**. Similarly, **b** must have the same units as **V**, or in this particular case the units of **cm³**

Example 6:

Your handbook shows that microchip etching roughly follows the relation

$$d = 16.2 - 16.2e^{-0.021t} \quad t < 200$$

where d is the depth of the etch in microns **(micrometers, µm)** and t is the time of the etch in seconds. What are the units associated with the numbers **16.2** and **0.021?** Convert the relation so that d becomes expressed in inches and t can be used in minutes.

Solution:

Both values of **16.2** must have the associated units of microns (**µm**). The exponential must be dimensionless so that **0.021** must have the associated units of $\mathbf{s^{-1}}$**.**

$$d_{\text{in}} = \frac{16.2\ \mu\text{m}}{}\left|\frac{1\ \text{m}}{10^6\ \mu\text{m}}\right|\frac{39.27\ \text{in.}}{1\ \text{m}}\left[1 - \exp\frac{-0.021}{s}\left|\frac{60s}{1\ \text{min}}\right|\frac{t_{\text{min}}}{}\right]$$
$$= 6.38 \times 10^{-4}(1 - e^{-1.26t_{\text{min}}})\ \text{inches}$$

Non dimensional Groups:

As you proceed with the study of chemical engineering, you will find that groups of symbols may be put together, either by theory or based on experiment, that have no net units. Such collections of variables or parameters are called **dimensionless or non-dimensional** groups. One example is the Reynolds number (group) arising in fluid mechanics.

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$$\text{Reynolds number} = \frac{Dv\rho}{\mu} = N_{RE}$$

where **D** is the pipe diameter, say in cm; ν is the fluid velocity, say in **cm/s**; ρ is the fluid density, say in **g/cm³**; and μ is
the viscosity, say in centipoise, units that can be converted to **g/(cm)(s).**
Introducing the consistent set of units for **D, ν, ρ**, and **μ** into **Dνρ/μ**, you will find that all the units cancel out so that the numerical value of 1 is the result of the cancellation of the units.

$$\frac{\cancel{cm}}{}\left|\frac{\cancel{cm}}{\cancel{s}}\right|\frac{\cancel{g}}{\cancel{cm^3}}\left|\frac{(\cancel{cm})(\cancel{s})}{\cancel{g}}\right.$$

Example 7:

Explain without differentiating why the following differentiation cannot be correct:

$$\frac{d}{dx}\sqrt{1 + (x^2/a^2)} = \frac{2ax}{\sqrt{1 + (x^2/a^2)}}$$

Where **x** is length and a is a constant.
Solution:

•Observe that x and a must have the same units because the ratio x2/a2 must be dimensionless (because 1 is dimensionless).

•Thus, the left-hand side of the equation has units of 1/x (from d/dx). However, the right-hand side of the
equation has units of x^2 (the product of ax).

•Consequently, something is wrong as the equation is not dimensionally consistent.

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H.W:

Questions

1. Which of the following best represents the force needed to lift a heavy suitcase?

a. 25 N b. 25 kN c. 250 N d. 250 kN

2. Pick the correct answer(s); a watt is

a. one joule per second b. equal to 1 (kg)(m^2)/s^2 c. the unit for all types of power

d. all of the above e. none of the above

3. Is kg/s a basic or derived unit in SI?

4. Answer the following questions yes or no. Can you

a. divide ft by s? b. divide m by cm? c. multiply ft by s? d. divide ft by cm? e. divide m by (deg) K? f. add

ft and s? g. subtract m and (deg) K h. add cm and ft? i. add cm and m^2? j. add 1 and 2 cm?

5. Why is it not possible to add 1 ft and 1 ft^2?

6. What is g_c?

7. Is the ratio of the numerator and denominator in a conversion factor equal to unity?

8. What is the difference, if any, between pound force and pound mass in the AE system?

9. Could a unit of force in the SI system be kilogram force?

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10. Contrast the procedure for converting units within the SI system with that for the AE system.

11. What is the weight of a one pound mass at sea level? Would the mass be the same at the center of Earth?

Would the weight be the same at the center of Earth?

12. What is the mass of an object that weighs 9.80 kN at sea level?

13. Explain what dimensional consistency means in an equation.

14. Explain why the so-called dimensionless group has no net dimensions.

15. If you divide all of a series of terms in an equation by one of the terms, will the resulting series of terms be

dimensionless?

16. How might you make the following variables dimensionless:

a. Length (of a pipe). b. Time (to empty a tank full of water).