CHAPTER 1

INTRODUCTION

This book is designed to give food technologists an understanding of the engineering principles involved in the processing of food products. They may not have to design process equipment in detail but they should understand how the equipment operates. With an understanding of the basic principles of process engineering, they will be able to develop new food processes and modify existing ones. Food technologists must also be able to make the food process clearly understood by design engineers and by the suppliers of the equipment used.

Only a thorough understanding of the basic sciences applied in the food industry - chemistry, biology and engineering - can prepare the student for working in the complex food industry of today. This book discusses the basic engineering principles and shows how they are important in, and applicable to, every food industry and every food process.

For the food process engineering student, this book will serve as a useful introduction to more specialized studies.

METHOD OF STUDYING FOOD PROCESS ENGINEERING

As an introduction to food process engineering, this book describes the scientific principles on which food processing is based and gives some examples of the application of these principles in several food industries. After understanding some of the basic theory, students should study more detailed information about the individual industries and apply the basic principles to their processes.

For example, after studying heat transfer in this book, the student could seek information on heat transfer in the canning and freezing industries.

To supplement the relatively few books on food-process engineering, other sources of information are used, for example:

- Specialist descriptions of particular food industries.

  These in general are written from a descriptive point of view and deal only briefly with engineering.

- Textbooks in chemical and biological process engineering.

  These are studies of processing operations but they seldom have any direct reference to food processing. However, the basic unit operations apply equally to all process industries, including the food industry.

- Engineering handbooks.

  These contain considerable data including some information on the properties of food materials.

- Periodicals.
  In these can often be found the most up-to-date information on specialized equipment and processes, and increased basic knowledge of the unit operations

A representative list of food processing and engineering textbooks is in the bibliography at the end of the book.

BASIC PRINCIPLES OF FOOD PROCESS ENGINEERING

The study of process engineering is an attempt to combine all forms of physical processing into a small number of basic operations, which are called unit operations. Food processes may seem bewildering in their diversity, but careful analysis will show that these complicated and differing processes can be broken down into a small number of unit operations. For example, consider heating of which innumerable instances occur in every food industry. There are many reasons for heating and cooling - for example, the baking of bread, the freezing of meat, the tempering of oils.

But in process engineering, the prime considerations are firstly, the extent of the heating or cooling that is required and secondly, the conditions under which this must be accomplished. Thus, this physical process qualifies to be called a unit operation. It is called 'heat transfer'.

The essential concept is therefore to divide physical food processes into basic unit operations, each of which stands alone and depends on coherent physical principles. For example, heat transfer is a unit operation and the fundamental physical principle underlying it is that heat energy will be transferred spontaneously from hotter to colder bodies.

Because of the dependence of the unit operation on a physical principle, or a small group of associated principles, quantitative relationships in the form of mathematical equations can be built to describe them. The equations can be used to follow what is happening in the process, and to control and modify the process if required.

Important unit operations in the food industry are fluid flow, heat transfer, drying, evaporation, contact equilibrium processes (which include distillation, extraction, gas absorption, crystallization, and membrane processes), mechanical separations (which include filtration, centrifugation, sedimentation and sieving), size reduction and mixing.

These unit operations, and in particular the basic principles on which they depend, are the subject of this book, rather than the equipment used or the materials being processed.

Two very important laws, which all unit operations obey, are the laws of conservation of mass and energy.

Conservation of Mass and Energy

The law of conservation of mass states that mass can neither be created nor destroyed. Thus in a processing plant, the total mass of material entering the plant must equal the total mass of material leaving the plant, less any accumulation left in the plant. If there is no accumulation, then the simple rule holds that "what goes in must come out". Similarly all material entering a unit operation must in due course leave.

For example, when milk is being fed into a centrifuge to separate it into skim milk and cream, under the law of conservation of mass the total number of kilograms of material (milk) entering the centrifuge per minute must equal the total number of kilograms of material (skim milk and cream) that leave the centrifuge per minute.

Similarly, the law of conservation of mass applies to each component in the entering materials. For example, considering the butter fat in the milk entering the centrifuge, the weight of butter fat entering the centrifuge per minute must be equal to the weight of butter fat leaving the centrifuge per minute. A similar relationship will hold for the other components, proteins, milk sugars and so on.

The law of conservation of energy states that energy can neither be created nor destroyed. The total energy in the materials entering the processing plant plus the energy added in the plant must equal the total energy leaving the plant.

This is a more complex concept than the conservation of mass, as energy can take various forms such as kinetic energy, potential energy, heat energy, chemical energy, electrical energy and so on.

During processing, some of these forms of energy can be converted from one to another. Mechanical energy in a fluid can be converted through friction into heat energy. Chemical energy in food is converted by the human body into mechanical energy.

Note that it is the sum total of all these forms of energy that is conserved.

For example, consider the pasteurizing process for milk, in which milk is pumped through a heat exchanger and is first heated and then cooled. The energy can be considered either over the whole plant or only as it affects the milk. For total plant energy, the balance must include: the conversion in the pump of electrical energy to kinetic and heat energy, the kinetic and potential energies of the milk entering and leaving the plant and the various kinds of energy in the heating and cooling sections, as well as the exiting heat, kinetic and potential energies.

To the food technologist, the energies affecting the product are the most important. In the case of the pasteurizer, the energy affecting the product is the heat energy in the milk. Heat energy is added to the milk by the pump and by the hot water passing through the heat exchanger. Cooling water then removes part of the heat energy and some of the heat energy is also lost to the surroundings.

The heat energy leaving in the milk must equal the heat energy in the milk entering the pasteurizer plus or minus any heat added or taken away in the plant.

Heat energy leaving in milk = initial heat energy
+ heat energy added by pump
+ heat energy added in heating section
- heat energy taken out in cooling section
- heat energy lost to surroundings.

The law of conservation of energy can also apply to part of a process. For example, considering the heating section of the heat exchanger in the pasteurizer, the heat lost by the hot water must be equal to the sum of the heat gained by the milk and the heat lost from the heat exchanger to its surroundings.

From these laws of conservation of mass and energy, a balance sheet for materials and for energy can be drawn up at all times for a unit operation. These are called material balances and energy balances.

Overall View of an Engineering Process

Using a material balance and an energy balance, a food engineering process can be viewed overall or as a series of units. Each unit is a unit operation. The unit operation can be represented by a box as shown in Fig. 1.1.

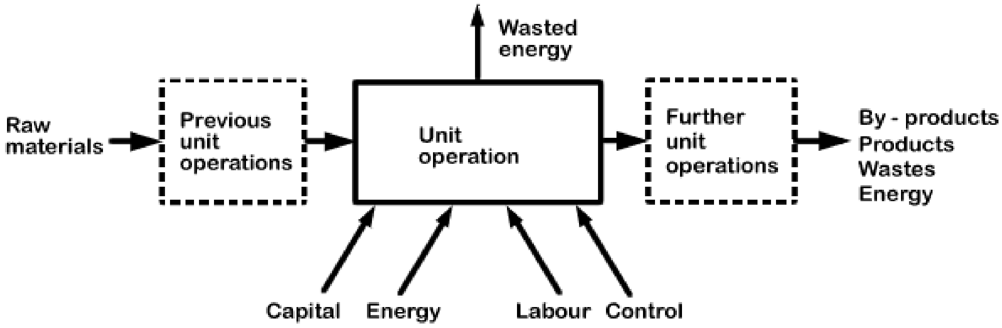

Figure 1.1 Unit operation

Into the box go the raw materials and energy, out of the box come the desired products, by-products, wastes and energy. The equipment within the box will enable the required changes to be made with as little waste of materials and energy as possible. In other words, the desired products are required to be maximized and the undesired by-products and wastes minimized. Control over the process is exercised by regulating the flow of energy, or of materials, or of both.

DIMENSIONS AND UNITS

All engineering deals with definite and measured quantities, and so depends on the making of measurements. We must be clear and precise in making these measurements.

To make a measurement is to compare the unknown with the known, for example, weighing a material compares it with a standard weight of one kilogram. The result of the comparison is expressed in terms of multiples of the known quantity, that is, as so many kilograms.

Thus, the record of a measurement consists of three parts: the dimension of the quantity, the unit which represents a known or standard quantity and a number which is the ratio of the measured quantity to the standard quantity.

For example, if a rod is 1.18 m long, this measurement can be analysed into a dimension, length; a standard unit, the metre; and a number 1.18 that is the ratio of the length of the rod to the standard length, 1 m.

To say that our rod is 1.18 m long is a commonplace statement and yet because measurement is the basis of all engineering, the statement deserves some closer attention. There are three aspects of our statement to consider: dimensions, units of measurement and the number itself.

Dimensions

It has been found from experience that everyday engineering quantities can all be expressed in terms of a relatively small number of dimensions. These dimensions are length, mass, time and temperature. For convenience in engineering calculations, force is added as another dimension.

Force can be expressed in terms of the other dimensions, but it simplifies many engineering calculations to use force as a dimension (remember that weight is a force, being mass times the acceleration due to gravity).

Dimensions are represented as symbols by: length [L], mass [M], time [t], temperature [T] and force [F].

Note that these are enclosed in square brackets: this is the conventional way of expressing dimensions.

All engineering quantities used in this book can be expressed in terms of these fundamental dimensions. All symbols for units and dimensions are gathered in Appendix 1.

For example:

Length = [L] area = $[L]^2$ volume = $[L]^3$

Velocity	= length travelled per unit time	=	$\frac{[L]}{[t]}$
Acceleration	= rate of change of velocity	=	$\frac{[L]}{[t]} \times \frac{1}{[t]} = \frac{[L]}{[t]^2}$
Pressure	= force per unit area	=	$\frac{[F]}{[L]^2}$
Density	= mass per unit volume	=	$\frac{[M]}{[L]^3}$
Energy	= force times length	=	[F] x [L]
Power	= energy per unit time	=	$\frac{[F] \times [L]}{[t]}$

As more complex quantities are needed, these can be analysed in terms of the fundamental dimensions. For example in heat transfer, the heat-transfer coefficient, *h*, is defined as the quantity of heat energy transferred through unit area, in unit time and with unit temperature difference:

$$h = \frac{[F] \times [L]}{[L]^2 [t] [T]} = [F] [L]^{-1} [t]^{-1} [T]^{-1}$$

Units

Dimensions are measured in terms of units. For example, the dimension of length is measured in terms of length units: the micrometre, millimetre, metre, kilometre, etc.

So that the measurements can always be compared, the units have been defined in terms of physical quantities. For example:

- the metre (m) is defined in terms of the wavelength of light;
- the standard kilogram (kg) is the mass of a standard lump of platinum-iridium;
- the second (s) is the time taken for light of a given wavelength to vibrate a given number of times;
- the degree Celsius (°C) is a one-hundredth part of the temperature interval between the freezing point and the boiling point of water at standard pressure;
- the unit of force, the newton (N), is that force which will give an acceleration of 1 m sec^{-2} to a mass of 1kg;
- the energy unit, the newton metre is called the joule (J), and
- the power unit, 1 J s^{-1}, is called the watt (W).

More complex units arise from equations in which several of these fundamental units are combined to define some new relationship. For example, volume has the dimensions $[L]^3$ and so the units are m^3. Density, mass per unit volume, similarly has the dimensions $[M]/[L]^3$, and the units kg/m^3. A table of such relationships is given in Appendix 1. When dealing with quantities which cannot conveniently be measured in m, kg, s, multiples of these units are used. For example, kilometres, tonnes and hours are useful for large quantities of metres, kilograms and seconds respectively. In general, multiples of 10^3 are preferred such as millimetres (m x 10^{-3}) rather than centimetres (m x 10^{-2}). Time is an exception: its multiples are not decimalized and so although we have micro (10^{-6}) and milli (10^{-3}) seconds, at the other end of the scale we still have minutes (min), hours (h), days (d), etc.

Care must be taken to use appropriate multiplying factors when working with these units. The common secondary units then use the prefixes micro (μ, 10^{-6}), milli (m,10^{-3}), kilo (k, 10^3) and mega (M, 10^6).

Dimensional Consistency

All physical equations must be dimensionally consistent. This means that both sides of the equation must reduce to the same dimensions. For example, if on one side of the equation, the dimensions are $[M] [L]/[T]^2$, the other side of the equation must also be $[M] [L]/[T]^2$ with the same dimensions to the same powers. Dimensions can be handled algebraically and therefore they can be divided, multiplied, or cancelled. By remembering that an equation must be dimensionally consistent, the dimensions of otherwise unknown quantities can sometimes be calculated.

EXAMPLE 1.1. Dimensions of velocity
In the equation of motion of a particle travelling at a uniform velocity for a time t, the distance travelled is given by $L = vt$. Verify the dimensions of velocity.

Knowing that length has dimensions [L] and time has dimensions [t] we have the dimensional equation:

$[v] = [L]/[t]$

<u>the dimensions of velocity must be $[L][t]^{-1}$</u>

The test of dimensional homogeneity is sometimes useful as an aid to memory. If an equation is written down and on checking is not dimensionally homogeneous, then something has been forgotten.

Unit Consistency and Unit Conversion

Unit consistency implies that the units employed for the dimensions should be chosen from a consistent group, for example in this book we are using the SI (Systeme Internationale de Unites) system of units. This has been internationally accepted as being desirable and necessary for the standardization of physical measurements and although many countries have adopted it, in the USA feet and pounds are very widely used. The other commonly used system is the fps (foot pound second) system and a table of conversion factors is given in Appendix 2.

Very often, quantities are specified or measured in mixed units. For example, if a liquid has been flowing at 1.3 l /min for 18.5 h, all the times have to be put into one only of minutes, hours or seconds before we can calculate the total quantity that has passed. Similarly where tabulated data are only available in non-standard units, conversion tables such as those in Appendix 2 have to be used to convert the units.

EXAMPLE 1.2. Conversion of grams to pounds
Convert 10 grams into pounds.

From Appendix 2, 1lb = 0.4536kg and 1000g = 1kg
so (1lb/ 0.4536kg) = 1 and (1kg/1000g) = 1
therefore 10g =10g x (1lb/0.4536kg) x (1kg/1000g)
= 2.2×10^{-2} lb
<u>10 g = 2.2×10^{-2} lb</u>

The quantity in brackets in the above example is called a conversion factor. Notice that within the bracket, and before cancelling, the numerator and the denominator are equal. In equations, units can be cancelled in the same way as numbers. Note also that although (1lb/0.4536kg) and (0.4536kg/1lb) are both = 1, the appropriate numerator/denominator must be used for the unwanted units to cancel in the conversion.

EXAMPLE 1.3. Velocity of flow of milk in a pipe.
Milk is flowing through a full pipe whose diameter is known to be 1.8 cm. The only measure available is a tank calibrated in cubic feet, and it is found that it takes 1 h to fill 12.4 ft^3. What is the velocity of flow of the liquid in the pipe in SI units?

Velocity is [L]/[t] and the units in the SI system for velocity are therefore m s^{-1}:

$v = L/t$ where v is the velocity.

Now $V = AL$ where V is the volume of a length of pipe L of cross-sectional area A

i.e. $L = V/A$.

Therefore $v = V/At$
Checking this dimensionally

$[L][t]^{-1} = [L]^3[L]^{-2}[t]^{-1} = [L][t]^{-1}$ which is correct.

Since the required velocity is in m s^{-1}, volume must be in m^3, time in s and area in m^2.
From the volume measurement

$V/t = 12.4 ft^3 h^{-1}$
From Appendix 2,
$1 ft^3 = 0.0283 m^3$
so $1 = (0.0283 m^3 / 1 ft^3)$
1 h = 60 x 60 s
so (1 h/3600 s) = 1

Therefore $V/t = 12.4 ft^3/h \times (0.0283 m^3/1 ft^3) \times (1 h/3600 s)$
$= 9.75 \times 10^{-5} m^3 s^{-1}$.

Also the area of the pipe $A = \pi D^2/4$
$= \pi(0.018)^2 /4 m^2$
$= 2.54 \times 10^{-4} m^2$

$v = V/t \times 1/A$
$= 9.75 \times 10^{-5}/2.54 \times 10^{-4}$
$= \underline{0.38 m s^{-1}}$

EXAMPLE 1.4. Viscosity (μ) conversion from fps to SI units
The viscosity of water at 60°F is given as 7.8×10^{-4} lb ft^{-1} s^{-1}.
Calculate this viscosity in N s m^{-2}.

From Appendix 2,
0.4536 kg = 1 lb
0.3048 m = 1 ft.

Therefore $7.8 \times 10^{-4} lb ft^{-1} s^{-1} = 7.8 \times 10^{-4} lb ft^{-1} s^{-1} \times \frac{0.4536 kg}{1 lb} \times \frac{1 ft}{0.3048m}$
$= 1.16 \times 10^{-3} kg m^{-1} s^{-1}$

Remembering that one Newton is the force that accelerates unit mass at $1ms^{-2}$

1 N = 1 kg m s^{-2}
therefore 1 N s m^{-2} = 1 kg m^{-1} s^{-1}

Required viscosity = 1.16×10^{-3} N s m^{-2}.

EXAMPLE 1.5. Thermal conductivity of aluminium: conversion from fps to SI units
The thermal conductivity of aluminium is given as 120 Btu ft^{-1} h^{-1} °F^{-1}. Calculate this thermal conductivity in J m^{-1} s^{-1} °C^{-1}.

From Appendix 2,
1 Btu = 1055 J
0.3048 m = 1 ft
°F = (5/9) °C.

Therefore 120 Btu ft^{-1} h^{-1} °F^{-1}

$$= 120\ \text{Btu ft}^{-1}\ \text{h}^{-1}\ °\text{F}^{-1} \times \frac{1055\ \text{J}}{1\ \text{Btu}} \times \frac{1\ \text{ft}}{0.3048\text{m}} \times \frac{1\text{h}}{3600\text{s}} \times \frac{1°\text{F}}{(5/9)°\text{C}}$$

$$= \underline{208\ \text{J m}^{-1}\ \text{s}^{-1}\ °\text{C}^{-1}}$$

Alternatively a conversion factor 1Btu ft^{-1} h^{-1} $°F^{-1}$can be calculated:

1Btu $ft^{-1}h^{-1}°F^{-1}$

$$= 1\text{Btu ft}^{-1}\ \text{h}^{-1}\ °\text{F}^{-1} \times \frac{1055\ \text{J}}{1\ \text{Btu}} \times \frac{1\ \text{ft}}{0.3048\ \text{m}} \times \frac{1\text{h}}{3600\text{s}} \times \frac{1°\text{F}}{(5/9)°\text{C}}$$

$$= 1.73\ \text{J m}^{-1}\ \text{s}^{-1}\ °\text{C}^{-1}$$

Therefore 120 Btu ft^{-1} h^{-1} $°F^{-1}$

$$= 120 \times 1.73\text{J m}^{-1}\ \text{s}^{-1}\ °\text{C}^{-1}$$

$$= \underline{208\ \text{J m}^{-1}\ \text{s}^{-1}\ °\text{C}^{-1}}$$

Because engineering measurements are often made in convenient or conventional units, this question of consistency in equations is very important. Before making calculations always check that the units are the right ones and if not use the necessary conversion factors. The method given above, which can be applied even in very complicated cases, is a safe one if applied systematically.

A loose mode of expression that has arisen, which is sometimes confusing, follows from the use of the word per, or its equivalent the solidus, /. A common example is to give acceleration due to gravity as 9.81 metres per second per second. From this the units of *g* would seem to be m/s/s, that is m s s^{-1} which is incorrect. A better way to write these units would be
$g = 9.81$ m/s^2 which is clearly the same as 9.81 m s^{-2}.

Precision in writing down the units of measurement is a great help in solving problems.

Dimensionless Ratios

It is often easier to visualize quantities if they are expressed in ratio form and ratios have the great advantage of being dimensionless. If a car is said to be going at twice the speed limit, this is a dimensionless ratio, which quickly draws attention to the speed of the car. These dimensionless ratios are often used in process engineering, comparing the unknown with some well-known material or factor.

For example, **specific gravity** is a simple way to express the relative masses or weights of equal volumes of various materials. The specific gravity is defined as the ratio of the weight of a volume of the substance to the weight of an equal volume of water.

SG = weight of a volume of the substance/ weight of an equal volume of water

$$\text{Dimensionally, SG} = \frac{[F]}{[L]^3} \div \frac{[F]}{[L]^3} = 1$$

If the density of water, that is the mass of unit volume of water, is known, then if the specific gravity of some substance is determined, its density can be calculated from the following relationship:

$$\rho = SG\ \rho_w$$

where ρ (rho) is the density of the substance, SG is the specific gravity of the substance and ρ_w is the density of water.

Perhaps the most important attribute of a dimensionless ratio, such as specific gravity, is that it gives an immediate sense of proportion. This sense of proportion is very important to food technologists as they are constantly making approximate mental calculations for which they must be able to maintain correct proportions. For example, if the specific gravity of a solid is known to be greater than 1 then that solid will sink in water. The fact that the specific gravity of iron is 7.88 makes the quantity more easily visualized than the equivalent statement that the density of iron is 7880 kg m^{-3}.

Another advantage of a dimensionless ratio is that it does not depend upon the units of measurement used, provided the units are consistent for each dimension.

Dimensionless ratios are employed frequently in the study of fluid flow and heat flow. They may sometimes appear to be more complicated than specific gravity, but they are in the same way expressing ratios of the unknown to the known material or fact. These dimensionless ratios are then called dimensionless numbers and are often called after a prominent person who was associated with them, for example Reynolds number, Prandtl number, and Nusselt number; these will be explained in the appropriate section.

When evaluating dimensionless ratios, all units must be kept consistent. For this purpose, conversion factors must be used where necessary.

Precision of Measurement

Every measurement necessarily carries a degree of precision, and it is a great advantage if the statement of the result of the measurement shows this precision. The statement of quantity should either itself imply the tolerance, or else the tolerances should be explicitly specified.

For example, a quoted weight of 10.1 kg should mean that the weight lies between 10.05 and 10.149 kg.
Where there is doubt it is better to express the limits explicitly as 10.1 ± 0.05 kg.

The temptation to refine measurements by the use of arithmetic must be resisted. For example, if the surface of a rectangular tank is measured as 4.18 m x 2.22 m and its depth estimated at 3 m, it is obviously unjustified to calculate its volume as 27.8388 m^3 which is what arithmetic or an electronic calculator will give. A more reasonable answer would be 28 m^3. Multiplication of quantities in fact multiplies errors also.

In process engineering, the degree of precision of statements and calculations should always be borne in mind. Every set of data has its least precise member and no amount of mathematics can improve on it. Only better measurement can do this.

A large proportion of practical measurements are accurate only to about 1 part in 100. In some cases factors may well be no more accurate than 1 in 10, and in every calculation proper consideration must be given to the accuracy of the measurements. Electronic calculators and computers may work to eight figures or so, but all figures after the first few may be physically meaningless. For much of process engineering three significant figures are all that are justifiable.

SUMMARY

1. Food processes can be analysed in terms of unit operations.

2. In all processes, mass and energy are conserved.

3. Material and energy balances can be written for every process.

4. All physical quantities used in this book can be expressed in terms of five fundamental dimensions [M] [L] [t] [F] [T].

5. Equations must be dimensionally homogeneous.

6. Equations should be consistent in their units.

7. Dimensions and units can be treated algebraically in equations.

8. Dimensionless ratios are often a very graphic way of expressing physical relationships.

9. Calculations are based on measurement, and the precision of the calculation is no better than the precision of the measurements.

PROBLEMS

1. Show that the following heat transfer equation is consistent in its units:

   $$q = UA\Delta T$$

   where q is the heat flow rate (J s^{-1}), U is the overall heat transfer coefficient (J $m^{-2}s^{-1}$°C^{-1}), A is the area (m^2) and ΔT is the temperature difference (°C).

2. The specific heat of apples is given as 0.86 Btu lb^{-1} °F^{-1}. Calculate this in J kg^{-1}°C^{-1}.

   (3600 J kg^{-1} °C^{-1} = 3.6 kJ kg^{-1} °C^{-1})

3. If the viscosity of olive oil is given as 5.6 x 10^{-2} lb$ft^{-1}s^{-1}$, calculate the viscosity in SI units.

   (83 x 10^{-3} kg$m^{-1}s^{-1}$ = 83 x 10^{-3} Nsm^{-2})

4. The Reynolds number for a fluid in a pipe is

   $$\frac{Dv\rho}{\mu}$$

   where D is the diameter of the pipe, v is the velocity of the fluid, ρ is the density of the fluid and μ is the viscosity of the fluid. Using the five fundamental dimensions [M], [L], [T], [F] and [t] show that this is a dimensionless ratio.

5. Determine the protein content of the following mixture, clearly showing the accuracy:

	% Protein	Weight in mixture
Maize starch	0.3	100 kg
Wheat flour	12.0	22.5 kg
Skim milk powder	30.0	4.31 kg

(3.4%)

6. In determining the rate of heating of a tank of 20% sugar syrup, the temperature at the beginning was 20^{o}C and it took 30min to heat to 80^{o}C. The volume of the sugar syrup was 50 ft^3 and its density 66.9 lbft^{-3}. The specific heat of sugar syrup is 0.9 Btu lb^{-1} °F^{-1}.
   (a) Convert the specific heat to kJ kg^{-1} °C^{-1}
   (b) Determine the average rate of heating, that is the heat energy transferred in unit time, in SI units (kJs^{-1})

   ((a) 3.7 kJ kg^{-1} °C^{-1} (b) 187 kJs^{-1})

7. The gas equation is $PV = nRT$.
   If P the pressure is 2.0 atm, V the volume of the gas is 6 m^3, R the gas constant is 0.08206 m^{3}atm mole^{-1} K^{-1} and T is 300 degrees Kelvin, what are the units of n and what is its numerical value?

   (0.49 moles)

8. The gas law constant R is given as 0.08206 m^3 atm mole^{-1} K^{-1}. Find its value in:
   (a) ft^{3}mm Hg lb-mole^{-1} K^{-1},
   (b) m^3 Pa mole^{-1} K^{-1},
   (c) Joules g-mole^{-1} K^{-1}.
   Assume 1atm. = 760mm Hg = 1.013x10^5 Nm^{-2}. Remember 1 joule = 1Nm and in this book, mole is kg mole.

   ((a) 999 ft^{3}mm Hg lb-mole^{-1} K^{-1} (b) 8313 m^3 Pa mole^{-1} K^{-1}(c) 8.313 J g-mole^{-1} K^{-1})

9. The equation determining the liquid pressure in a tank is $z = P\rho g$ where z is the depth, P is the pressure, ρ is the density and g is the acceleration due to gravity. Show that the two sides of the equation are dimensionally the same.

10. The Grashof number (Gr) arises in the study of natural convection heat flow. If the number is given as:

$$\frac{D^3\rho^2\beta g\Delta T}{\mu^2}$$

   verify the dimensions of β the coefficient of expansion of the fluid. The symbols are all defined in Appendix 1.

   ([T]$^{-1}$)