INTRODUCTION TO MATERIAL HANDLING AND TRANSPORTATION-SELECTION OF MATERIAL HANDLING MACHINES AND CONVEYORS, BELT CONVEYOR; BELT CONVEYOR IDLERS, IDLER SPACING, BELT TENSION

**Material handling Equipment**

**Material handling** includes several operations that can be executed either by hand (manual) or by mechanical means or devices to convey material and to reduce the human drudgery.

The most common types of mechanical devices for grain handling are;

1. Belt conveyor
2. Bucket elevator
3. Screw conveyor
4. Chain Conveyor
5. Pneumatic conveyor

**Selection of material Handling machines and Conveyors**

The selection of proper conveying system is important for ease in operation and getting desired capacity for a product. Principles based on which the material handling equipment is selected:

Based on the characteristics of the products being conveyed

Working and climatic conditions.

The capacity of conveying

In a conveying system possibility of use of gravity.

The capacity of handling / conveying equipment should match with the capacity of processing unit or units.

Spillage of conveyed products should be avoided.

Pollution of the environment due to noise or dust by the conveying system should also be avoided.
**Belt conveyors**

A belt conveyor is an endless belt operating between two pulleys with its load supported on idlers. The belt may be flat for transporting bagged material or V-shaped. The belt conveyor consists of a belt, drive mechanism and end pulleys, idlers and loading and discharge devices (Fig. 1.1)

![Diagram of a belt conveyor](image)

**Fig.1.1 Diagram of a belt conveyor**

On the belt conveyor baggage/product lie still on the surface of belt and there is no relative motion between the product and belt. This results in generally no damage to material. Belt can be run at higher speeds, so, large carrying capacities are possible. Horizontally the material can be transported to longer distance. The initial cost of belt conveyor is **high for short distances**, but for longer distances the initial cost of belt conveying system is low.

The first step in the design of a belt conveyor with a specified conveying capacity is to determine the speed and width of the belt.

The belt speed should be selected to minimise product spillage or removal of fines due to velocity of the belt. For transportation of grains, the belt speed should not increase 3.5 m/s. Generally, for grain conveying, belt speed of 2.5 to 2.8 m/s is recommended. The selection of belt width will depend upon the capacity requirement, speed of operation, angle of inclination of belt conveyor, trough angle and depth. The capacity of belt conveyor can be calculated as:

\[
\text{Capacity, } m^2/h = (\text{area of cross-section, } m^2) \times (\text{belt-speed, } m/min) \times 60
\]

**Belt conveyor idlers:** The efficiency of belt conveyor is largely dependent on idlers. For higher efficiency of belt conveying systems, the idlers must be accurately made and provide a rigid framework. This will maintain a permanent, well balanced smooth running alignment.
There are three kinds of belt carrying idlers which are used in handling of bulk materials. The type of idlers affects the cross-sectional load on the belt.

1. The **flat belt idlers** are used for granular materials having an angle of repose of not less than 35°.

2. **Troughing idlers with 20° trough** is used for conveying all kinds of bulk materials.

3. **Troughing idlers with 35° and 45° trough angle** is mainly used for transportation of small particle light weight materials like grain, cotton seed etc. It is also used for carrying heavier, medium size lumps like crushed stones.

**Idler Spacing**

The spacing between the idlers influences the retention of correct troughing. The incorrect idler spacing may result in belt undulation. The pitch of idlers is determined by the idler load rating or the carrying capacity of each idler, on the sag of the belt between the idlers, belt tension and belt speed. **As a token, the space between the successive idlers should be approximately equal to the width of belt. The spacing should not exceed 1·2 metres.**

**Belt tension**
The tension developed at the drive pulley in transmitting the required power to move the loaded belt is known as effective tension. The effective tension is the sum of tension to move the empty belt, the tension to move the load horizontally and the tension to lift the material. The effective tension is related with the power required to move the belt and belt speed in the following manner.

\[
\text{Effective Tension, } T_e = \frac{\text{Power in kW}}{\text{belt Speed, } m/s}
\]

Grains are mostly discharged from the belt conveyor over the end pulley or at any other point along the conveyor by a scraper plough or a throw-off carriage known as a tripper.

While leaving the belt over the end pulley, product flow will describe the path of a parabola.

Belt conveyors can discharge grains at various locations by means of a movable tripper (Fig.1.3). Trippers are available as hand propelled, self propelled or automatic.

![Tripper for discharge of materials](image)
SCREW CONVEYOR: SCREW CONVEYOR DETAILS, VARIOUS SHAPES OF SCREW CONVEYOR TROUGH, CAPACITY AND HORSE POWER

**Screw Conveyor**

The screw conveyor consists of a tubular or U-shaped trough in which a shaft with spiral screw revolves. The screw shaft is supported hanger bearings at ends. The rotation of screw pushes the grain along the trough. A typical screw conveyor is shown in the following Figure. The screw conveyor is used in grain handling facilities, animal feed industries and other installations for conveying of products generally for short distances. Screw conveyor requires relatively high power and is more susceptible to wear than other types of conveyors. The pitch of a standard screw which is the distance from the centre of one thread to the centre of the next thread is equal to its diameter. For example a 10 cm diameter screw has a pitch of 10 cm.

![Fig.3.1 Screw conveyor](image1)

**Fig.3.1 Screw conveyor**

![Fig. 3.2 Screw conveyor details](image2)

**Fig. 3.2 Screw conveyor details**
1. screw diameter 2. pitch of screw 3. screw length

As the screw conveyor's driving mechanism is simpler, and no tensioning device is required, the initial cost of the conveyor is lower than any other conveyor with the same length and capacity. The main parts of a screw
conveyor are, screw blade, screw shaft, coupling, trough, cover, inlet and outlet gates, bearings and drive mechanism.

The screw conveyor is generally used to move grains horizontally. However, it can also be used at any angle up to 90° from the horizontal, but the capacity correspondingly reduced as per the inclination of conveyance.

The screw basically consists of a shaft and the screw blade or flight. The flight is a continuous one piece helix shaped from a flat strip of steel welded onto the shaft. The screw shaft is usually a joint less tube with thick sides and a high tensile strength to reduce the weight. The thickness of the steel strip helix decreases from the inner edge to the outer edge. Troughs of screw conveyor have different shapes. Most common is U shaped trough. In an enlarged or flared trough the side walls become wider at the top (Figure). This type of trough is usually used for conveying non-easy flowing materials which may have lumps. The tubular trough is completely closed with circular cross-section and mostly used for conveying materials at inclination or for vertical lift.

![Fig.3.3 Various shapes of screw conveyor trough](image)

I. U-trough II. Flared trough III. tubular trough

If the screw conveyor is used to convey different materials, mixing of products is possible. The capacity of screw conveyor is influenced by the screw diameter, inclination of the screw blade, speed of the blade, shaft diameter and cross-section of loading. The theoretical conveyance capacity of the screw conveyor can be given by the following equation.

Capacity \( Q, \text{m}^3/\text{hr} = 47.2 \times (D^2 - d^2) \times P \times n \)

where,

\( D = \) screw diameter, \( m \)
\( d = \) shaft diameter, \( m \)
\( p = \) pitch, \( m \)
\( n = \) rpm
The theoretical capacity is more than the actual capacity because of screw housing clearance and the loading factor (Figure 3.4).

![Figure 3.4 Screw conveyor loading factor](image)

I. 30% loading  
II. 55% loading

The power requirement of screw conveyors for horizontal operation is determined by the following equation.

Horse power = \( \frac{QLWF}{4560} \)

where,  
- \( Q \) = conveyor capacity, \( m^3/hr \)  
- \( L \) = conveyor length, m  
- \( W \) = bulk material weight, \( kg/m^3 \)  
- \( F \) = material factor (for paddy 0.4)

If the calculated horsepower is less than 1.0, double the value.

- horse power = 1 to 2 multiply the value by 1.5  
- horse power = 2 to 4 multiply the value by 1.25  
- horse power= 4 to 5 multiply the value by 1.1

For horsepower values of more than 5, no correction is required.
PNEUMATIC CONVEYOR, LIMITATIONS OF PNEUMATIC CONVEYING, CHAIN CONVEYOR

Pneumatic Conveyor

The pneumatic conveyor moves granular materials in a closed duct by a high velocity air stream. Pneumatic conveying is a continuous and flexible transportation method. The material is carried in pipelines either by suction or blowing pressure of air stream. The granular materials because of high air pressure are conveyed in dispersed condition. For dispersion of bulk material, air velocities in the range of 15-30 m/s is necessary.

The pneumatic conveying system needs a source of air blowing or suction, means of feeding the product into the conveyor, ducts and a cyclone or receiving hopper for collection of product. There are three basic systems of pneumatic conveying. These are pressure or blowing system, suction or vacuum system, and combined push-pull or suck blow system.

In blowing or positive pressure systems, the product is conveyed by using air pressures greater than the atmospheric pressure.

The selection of air mover is the most important aspect of the design of a pneumatic conveying system. In design, the two factors, (1) supply air pressure and (2) the volumetric flow rate of air should be considered.

For separation of product particles from air, air-product separators are used. Cyclones are mostly used to collect the particles. Cyclone is a device which removes the bulk of the product particle from the conveying air stream by centrifugal force. In some cyclone, a fabric filter is attached to remove residual dust and fine product particles from the air stream (Figure 4.1).

![Fig. 4.1 Separation of product particles from air by means of a fabric filter](image)
**Limitations of Pneumatic Conveying**

1. Erosion of solid surfaces and equipment surfaces by solid particles with conveying air stream.
2. In case of bends or misaligned sections, the erosion problem becomes severe.
3. Chances of repeated impacts between the particles and the solid surfaces are high. Due to such impacts, product degradation results.

**Chain Conveyor**

A chain is a reliable machine component, which transmits power by means of tensile forces, and is used primarily for power transmission and conveyance systems. The function and uses of chain are similar to a belt. Chains are divided into five types based on material of composition or method of construction.

- Cast iron chain
- Cast steel chain
- Forged chain
- Steel chain
- Plastic chain
PRETREATMENT UNIT OPERATIONS: CLEANING, SORTING: FIXED APERTURE SORTING

Pretreatment Unit Operations

At the time of harvest or slaughter, most foods are likely to contain contaminants, to have components which are inedible or to have variable physical characteristics (for example shape, size or colour). It is therefore necessary to perform one or more of the unit operations of cleaning, sorting, grading or peeling to ensure that foods with a uniformly high quality are prepared for subsequent processing.

Cleaning

Cleaning is the unit operation in which contaminating materials are removed from the food and separated to leave the surface of the food in a suitable condition for further processing. A classification of the type of contaminants found on raw foods is shown in the following Table.

Table Contaminants found on raw foods

<table>
<thead>
<tr>
<th>Type of contaminant</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td>Ferrous and non-ferrous metals, bolts, filings</td>
</tr>
<tr>
<td>Mineral</td>
<td>Soil, engine oil, grease, stones</td>
</tr>
<tr>
<td>Plant</td>
<td>Leaves, twigs, weed seeds, pods and skins</td>
</tr>
<tr>
<td>Animal</td>
<td>Hair, bone, excreta, blood, insects, larvae</td>
</tr>
<tr>
<td>Chemical</td>
<td>Fertilizer, pesticides, herbicides</td>
</tr>
<tr>
<td>Microbial cells</td>
<td>Soft rots, fungal growth, yeasts</td>
</tr>
<tr>
<td>Microbial products</td>
<td>Colors, flavors, toxins</td>
</tr>
</tbody>
</table>

Peeling fruits and vegetables, skinning meat or descaling fish are also considered as cleaning operations. In vegetable processing, blanching helps to clean the product. Cleaning should take place at the earliest opportunity in a food process both to prevent damage to subsequent processing equipment by stones, bone or metals, and to prevent time and money from being spent on processing contaminants which are then discarded. In addition, the early removal of small quantities of food contaminated by micro-organisms prevents the subsequent loss of the remaining bulk by microbial growth during storage or
delays before processing. Cleaning is thus an effective method of reducing food wastage, improving the economics of processing and protecting the consumer.

**Equipment for cleaning is categorized into** wet procedures (for example soaking, spraying, flotation washing and ultrasonic cleaning) and dry procedures (separation by air, magnetism or physical methods).

**Wet cleaning**

Wet cleaning is more effective than dry methods for removing soil from root crops or dust and pesticide residues from soft fruits or vegetables. It is also dustless and causes less damage to foods than dry methods. Different combinations of detergents and sterilants at different temperatures allow flexibility in operation. However, the use of warm cleaning water may accelerate chemical and microbiological spoilage unless careful control is exercised over washing times and subsequent delays before processing.

Furthermore wet procedures produce large volumes of effluent, often with high concentrations of dissolved and suspended solids (measured as biological oxidation demand (BOD) or chemical oxidation demand (COD)). Examples of wet-cleaning equipment include spray washers, brush washers, drum or rod washers, ultrasonic cleaners and flotation tanks.

**Dry cleaning**

Dry cleaning procedures are used for products that are smaller, have greater mechanical strength and possess lower moisture content (for example grains and nuts). After cleaning, the surfaces are dry, to aid preservation or further drying. Dry procedures generally involve smaller cheaper equipment than wet procedures do and produce a concentrated dry effluent which may be disposed of more cheaply.

The main groups of equipment used for dry cleaning are:

- air classifiers
- magnetic separators
- separators based on screening of foods

**Removing contaminants and foreign bodies**

Physical separation of contaminants from foods is possible when the food has a regular well-defined shape. For example round foods (peas, blackcurrants and rapeseed) are separated from contaminants by exploiting their ability to roll
down an inclined, upward moving conveyor belt. A disc separator, used to separate grain from weed seeds, consists of a series of vertical metal discs with precisely engineered indentations in the sides that match the shape of the grain. Screens are also used to remove contaminants from foods.

![Diagram](image)

**Fig. 5.1** Separation of chaff from grain by aspiration cleaning.

Contamination by metal fragments or bolts from machinery is a potential hazard in all processing. Raw materials may pass through metal detectors before processing and all packaged foods are checked for contamination. **Ferrous metals** are removed by either permanent magnets or electromagnets. Electromagnets are easier to clean (by switching off the power supply) but permanent magnets are cheaper.

**Sorting**

Sorting is the separation of foods into categories on the basis of a measurable physical property. Like cleaning, sorting should be employed as early as possible to ensure a uniform product for subsequent processing. The four main physical properties used to sort foods are size, shape, weight and colour.

**Shape and size sorting**

The particle size distribution of a material is expressed as either the mass fraction of material that is retained on each sieve or the cumulative percentage of material retained.
The shape of some foods is important in determining their suitability for processing or their retail value. For example, for economical peeling, potatoes should have a uniform oval or round shape without protuberances. Shape sorting is accomplished either manually or mechanically. **Size sorting** (termed *sieving or screening*) is the separation of solids into two or more fractions on the basis of differences in size. It is particularly important when the food is to be heated or cooled as the rate of heat transfer is in part determined by the size of the individual pieces and variation in size would cause over-processing or under-processing. Additionally, foods which have a uniform size are said to be preferred by consumers.

Screens with either **fixed or variable apertures** are used for size sorting. The screen may be stationary or, more commonly, rotating or vibrating. **Fixed aperture screens**

Two common types of fixed aperture screen are the flat bed screen (or sieve) and the drum screen (rotary screen or reel). The multideck flat bed screen (Figure 5.3) has a number of inclined or horizontal mesh screens, which have aperture sizes from 20 \( \, \text{mm} \) to 125 mm, stacked inside a vibrating frame. Food particles that are smaller than the screen apertures pass through under gravity until they reach a screen with an aperture size that retains them. The smallest particles that are separated commercially are of the order of 50 \( \, \text{m} \).
The capacity of a screen is the amount of food that passes through per square metre per second.

The rate of separation is controlled by:

- the shape and size distribution of the particles
- the nature of the sieve material
- the amplitude and frequency of shaking
- the effectiveness of methods used to prevent blocking (or blinding) of the sieves.

These types of screens are widely used for sorting dry foods (for example flour, sugar and spices).

The main problems encountered are:

- excessive moisture or high humidity, which causes small particles to stick to the screen or to agglomerate and form larger particles, which are then discharged as oversize
- blinding, particularly if the particle size is close to that of the screen aperture
- high feed rates, which cause the screens to become overloaded and small particles, are discharged with the oversized particles.

Where vibration alone is insufficient to separate particles adequately, a gyratory movement is used to spread the food over the entire sieve area, and a vertical jolting action breaks up agglomerates and dislodges particles that block sieve apertures.
Many types of drum screen are used for sorting small-particulate foods (for example nuts, peas or beans) that have sufficient mechanical strength to withstand the tumbling action inside the screen. Drum screens are almost horizontal (5–10° inclination), perforated metal or mesh cylinders. They may be **concentric** (one inside another), **parallel** (foods leave one screen and enter the next (Figure 5.4)) or **series** (a single drum constructed from sections with different sized apertures). All types have a higher capacity than flat bed screens and problems associated with blinding are less severe than with flat bed screens. The capacity of drum screens increases with their speed of rotation up to a critical point. Above this the food is held against the screen by centrifugal force and results in poor separation. Similarly there is an increase in capacity with the angle of the screen up to a critical angle. Above this the residence time is too short and products pass through without separation.

Fig. 5.4 Parallel drum screen.
SORTING: VARIABLE APERTURE SCREENS, IMAGE PROCESSING, COLOR SORTING, WEIGHT SORTING AND GRADING

Variable-aperture screens

Variable-aperture screens have either a continuously diverging aperture or a stepwise increase in aperture. Both types handle foods more gently than drum screens and are therefore used to sort fruits and other foods that are easily damaged. Continuously variable screens employ pairs of diverging rollers, cables or felt-lined conveyor belts. These may be driven at different speeds to rotate the food and thus to align it, to present the smallest dimension to the aperture (Figure).

![Figure 6.1 Sorting lemons on a roller sorter.](image)

Stepwise increases in aperture are produced by adjusting the gap between driven rollers and an inclined conveyor belt (Refer Figure on belt and roller sorter). The food rotates and the same dimension is therefore used as the basis for sorting (for example the diameter along the core of a fruit).

Image processing

Image processing is used to sort foods on the basis of length, diameter, and number of surface defects and orientation of the food on a conveyor as well as colour. It has been used for example with maize cobs, which pass beneath
three video cameras, placed 120° apart above a conveyor belt. The images of the surface of the cob are recorded and stored in the memory of a microprocessor. The information is then analyzed and compared with pre-programmed specifications for the product, and the cob is either rejected or moved into a group with similar characteristics.

**Colour sorting**

Manual sorting by colour is still widely used but is increasingly expensive in both labour costs, operator training and the space required for sorting tables. There has therefore been considerable development of machine vision sorting systems which are said to have lower operating costs and greater accuracy than manual methods. These include monochrome (black and white), bichrome (4100 shades of red and green) and trichromatic or full colour (262,000 shades of red, green and blue, with optional infrared). Each is controlled by a programmable logic controller which has pre-set programs for different products that are easily changeable by operators using a video display. They are used for example, to sort potatoes for defects and blemishes by identifying dark areas on the potato surface. Light sensitive cells in the camera (termed ‘pixels’) **produce a voltage that is proportional to the intensity of light received. An electronic circuit that receives a lower voltage than the pre-set value can thus detect darker objects or areas which reflect less light than normal.** The voltage produced in the electronic circuit can be adjusted to alter the sensitivity of detection. Up to 10 tonnes of product per hour pass beneath the cameras on conveyors operating at 150–180 m per min. **Defective items are removed by electronically controlled air jets that can operate for 20 milliseconds, thus covering 50 mm of the belt length in a single blast.** In another system, vegetables in free-fall are scanned 1000 times per second, as they leave a conveyor belt, using concentrated helium-neon or laser light beams and a high-speed rotating mirror. The machine detects differences in reflectivity between good product and unwanted material.

Small-particulate foods may be automatically sorted at high rates using microprocessor controlled colour sorting equipment. Particles are fed into the chute one at a time. The angle, shape and lining material of the chute are altered to control the velocity of the pieces as they pass a photodetector. The colour of the background and the type and intensity of the light used for illuminating the food (including infrared and ultraviolet options) are closely controlled for each product.
Photodetectors measure the reflected colour of each piece and compare it with pre-set standards, and defective foods are separated by a short blast of compressed air. The computer can store 100 named product configurations to enable rapid changeover to different products using an operator touchpad.

Typical applications include peanuts, rice, diced carrot, maize kernels, cereals, snack foods and small fruits.

A different type of equipment employs a sensor located above a conveyor belt, which views products as they pass beneath. The sensor detects up to eight colours and provides an alarm or control signal whenever a pre-selected colour passes the detector beam. It is also able to distinguish between different coloured foods which are to be processed separately. In a more sophisticated system, foods which have variations in colour over their surface are colour sorted by image processing. The foods are fed in rows on a roller conveyor beneath a video camera. The relative intensities of reflected red, green and yellow light are transmitted to the microcomputer which constructs a composite image of each piece of food, showing both the spread of colour and the mean colour of inspected foods. The computer compares the constructed image with pre-set specifications and activates a compressed air ejector or a mechanical
deflector to remove rejected food. When this type of system is used to sort baked goods, it is also used to control directly the gas or electricity supply to the ovens, which is reported to reduce energy consumption in ovens by 20%. The sorter can be easily adapted to different foods, by operators using the microprocessor keypad.

**Weight sorting**

Weight sorting is more accurate than other methods and is therefore used for more valuable foods (for example eggs, cut meats and some tropical fruits). Eggs are sorted at up to 12 000 per hour into six to nine categories with a tolerance of 0.5 g. They are first graded by ‘candling’ and then pass to the weight sorter. This consists of a slatted conveyor which transports the eggs above a series of counterbalanced arms. The conveyor operates intermittently and while stationary, the arms raise and weigh the eggs. Heavy eggs are discharged into a padded chute and lighter eggs are replaced on the conveyor to travel to the next weigher.

**Aspiration** and **flotation** sorting use differences in density to sort foods and are similar in principle and operation to aspiration and flotation cleaning. Grains, nuts and pulses are sorted by aspiration. Peas and lima beans are sorted by flotation in brine (specific gravity, 1.1162–1.1362). The denser, starchy, over-mature pieces sink whereas the younger pieces float.

![Egg sorter](image)

**Fig. Egg sorter.**

**Grading**

This term is often used interchangeably with sorting but strictly means ‘the assessment of overall quality of a food using a number of attributes’. Sorting (that is separation on the basis of one characteristic) may therefore be used as part of a grading operation but not vice versa. Grading is carried out by operators
who are trained to simultaneously assess a number of variables. For example, **eggs** are visually inspected over tungsten lights (termed ‘candling’) to assess up to twenty factors and remove those that are for example, fertilized or malformed and those that contain blood spots or rot. Meats, for example, are examined by inspectors for disease, fat distribution, bone to flesh ratio and carcass size and shape. Other graded foods include cheese and tea, which are assessed for flavour, aroma, colour, etc. Apples are graded with the assistance of coloured cards that show the required characteristics of different grades in terms of colour distribution across the fruit, surface blemishes and size and shape of the fruit.

In some cases the grade of food is determined from the results of laboratory analyses (for example wheat flour is assessed for protein content, dough extensibility, colour, moisture content and presence of insects). In general, grading is more expensive than sorting owing to the higher costs of skilled operators. However, many attributes that cannot be examined automatically can be simultaneously assessed, and this produces a more uniform high-quality product.
PEELING, DEHULLING, DEHUSKING

**Peeling**

Peeling is used in the processing of many fruits and vegetables to remove unwanted or inedible material, and to improve the appearance of the final product. The main consideration is to minimise costs by removing as little of the underlying food as possible and reducing energy, labour and material costs to a minimum. The peeled surface should be clean and undamaged.

There are five main methods of peeling:

1. flash steam peeling
2. knife peeling
3. abrasion peeling
4. caustic peeling
5. flame peeling.

1. **Flash steam peeling**

Foods (for example root crops) are fed in batches into a pressure vessel which is rotated at 4 – 6 rpm. High-pressure steam \((1500 \times 10^3 \text{ Pa})\) is introduced and all food surfaces are exposed to the steam by the rotation of the vessel for a predetermined time, which differs according to the type of food. The high temperatures cause rapid heating of the surface layer (within 15–30 s) but the low thermal conductivity of the product prevents further heat penetration, and the product is not cooked. Texture and colour are therefore preserved. The pressure is then instantly released which causes steam to form under the skin, and the surface of the food ‘flashes off’. Most of the peeled material is discharged with the steam, and water sprays are needed only to remove any remaining traces. This type of peeler is gaining in popularity owing to the lower water consumption, minimum product loss, good appearance of the peeled surfaces, a high throughput (up to 4500 kg/h) with automatic control of the peeling cycle, and the production of a more easily disposable concentrated waste.

**Knife peeling**

Stationary blades are pressed against the surface of rotating fruits or vegetables to remove the skin. Alternatively the blades may rotate against
stationary foods. This method is particularly suitable for citrus fruits where the skin is easily removed and there is little damage or loss of fruit.

**Abrasion peeling**

Food is fed onto carborundum rollers or placed into a rotating bowl which is lined with carborundum. The abrasive surface removes the skin and it is washed away by a copious supply of water. The advantages of the method include low energy costs as the process operates at room temperature, low capital costs, no heat damage and a good surface appearance of the food. Irregular product surfaces (for example ‘eyes’ on potatoes) may mar the appearance of the peeled product and require hand finishing.

The limitations of the method are:

- a higher product loss than flash peeling (25% compared with 8–18% losses, for vegetables)
- the production of large volumes of dilute waste which are difficult and expensive to dispose of
- relatively low throughputs as all pieces of food need to contact the abrasive surfaces.

**Caustic peeling**

A dilute solution of sodium hydroxide (named lye) is heated to 100–120°C. In the older method of lye peeling, food is passed through a bath of 1–2% lye which softens the skin and the skin is then removed by high-pressure water sprays. Product losses are of the order of 17%. Although once popular for root crops, this method causes changes in the colour of some products and incurs higher costs. It is now largely replaced by steam or flash peeling.

A development of lye peeling is named dry caustic peeling. Food is dipped in 10% sodium hydroxide and the softened skin is removed with rubber discs or rollers. This both reduces water consumption and product losses and gives a concentrated skin ‘paste’ which is more easily disposed of.

**Flame peeling**

Developed for onions, this peeler consists of a conveyor belt which carries and rotates the food through a furnace heated to 1000 °C. The outer ‘paper shell’ and root hairs are burned off, and the charred skin is removed by high-pressure water sprays. Average product losses are 9%.
Dehulling and Dehusking

Dehulling is the process of removing the hulls (or chaff) from beans and other seeds. This is done using a machine known as a huller. To prepare the seeds to have oils extracted from them, they are cleaned to remove any foreign objects. Next, the seeds have their hulls, or outer coverings, or husk, removed.

Brown rice is produced by removing the husk from the paddy rice. The husk is removed by friction as the paddy grains pass between two abrasive surfaces that are moving at different speeds. After dehusking, the husk is removed by suction and transported to a storage dump outside the mill. Husk accounts for 20% of the paddy weight and an efficient husker should remove 90% of the husk in a single pass.

Rice hulling and shelling are different processes. So far in both the condition the major aim is milling of paddy to get rice. Shelling of paddy is such a term where the operation of taking out husk from paddy is known while hulling or dehusking is that process where not only husk is separated but some part of grain embryo and bran is also separated.
MIXING: INTRODUCTION, AGITATION, AGITATED VESSELS, MIXING OF LIQUIDS

Mixing
Mixing is the dispersing of components, one throughout the other. The mixing of liquids, solids and gases is one of the commonest of all operations in the food processing industries. Of the possible combinations of these states, those of principal interest are liquid/liquid mixtures, solid/solid mixtures, and liquid/solid mixtures or pastes.

Reasons for mixing are:
- to bring about intimate contact between different species in order for a chemical reaction to occur; and
- to provide a new property of the mixture which was not present in the original separate components. An example is a food mixture of a given component for nutritional purposes.

It should be clear from the foregoing that mixing is brought about by agitation.

There are three criteria by which the performance of a mixer should be assessed. These are:
1. the degree of mixedness achieved,
2. the time required to bring about mixing, and,
3. the power consumption required.

Agitation
The agitation of a liquid is defined as the establishment of a particular flow pattern within the liquid, usually a circulatory motion within a container. Mixing is brought about by agitation.

Purposes of agitation
Liquids are agitated for a number of purposes, depending on the objectives of the processing step. These purposes include:
1. Suspending solid particles.
2. Blending miscible liquids, for example, methyl alcohol and water.
3. Dispersing a gas through the liquid in the form of small bubbles.
4. Dispersing a second liquid, immiscible with the first, to form an emulsion or a suspension of fine drops.
5. Promoting heat transfer between the liquid and a coil or jacket.

**AGITATED VESSELS**

Liquids are most often agitated in some kind of tank or vessel, usually cylindrical in form and with a vertical axis. The top of the vessel may be open to the air; more usually it is closed. The proportions of the tank vary widely, depending on the nature of the agitation problem. A standardized design such as that shown in the following figure however, is applicable in many situations. The tank bottom is rounded, not flat, to eliminate sharp corners or regions into which fluid currents would not penetrate. The liquid depth is approximately equal to the diameter of the tank. An impeller is mounted on an overhung shaft, that is, a shaft supported from above. The shaft is driven by a motor, sometimes directly connected to the shaft but more often connected to it through a speed reducing gearbox. Accessories such as inlet and outlet lines, coils, jackets, and wells for thermometers or other temperature-measuring devices are usually included.

![Image of an agitated vessel](image)

**Figure 8.1 Typical Agitation Process Vessel**

The impeller causes the liquid to circulate through the vessel and eventually return to the impeller. Baffles are often included to reduce tangential motion.
Mixing of Liquids - Liquid Mixing Equipment

For the deliberate mixing of liquids, the propeller mixer is the most common and the most satisfactory. In using propeller mixers, it is important to avoid regular flow patterns such as an even swirl round a cylindrical tank, which may accomplish very little mixing. To break up these streamline patterns, baffles are often fitted, or the propeller may be mounted asymmetrically.

The mixing of liquids is achieved in an agitated tank. A large number of different types of impellers are in use; different impellers impart different flow patterns to the liquid and they must be matched to the rheology of the liquid and to the desired shear rate. Mixing vessels usually have rounded bottoms, rather than flat ones, to prevent the formation of dead spaces. The liquid depth is normally equal to the tank diameter. When an impeller rotates in a liquid the liquid is likely to swirl in a mass and a vortex will form (Figure). This is undesirable; the vortex may well draw air from the surface down to the impeller with the possibility either of unwanted dissolution of air or a waste of energy as the impeller rotates partly in air at the expense of agitating the liquid. Consequently baffles are fitted to the tank which consists of vertical strips of metal running the full depth of the inside surface of the tank. Normally four baffles are used, their width being about 10% of the tank diameter. Baffles minimize vortex formation, prevent swirling of the liquid, and result in more rapid mixing.

Figure 8.2 Paddle impeller
Figure 8.3 Anchor impeller

Figure 8.4 Gate Impeller

Figure 8.5 Helical Impeller

Figure 8.6 Vortex formation: without baffles
Various baffles can be used and the placing of these can make very considerable differences to the mixing performances. It is tempting to relate the amount of power consumed by a mixer to the amount of mixing produced, but there is no necessary connection and *very inefficient mixers can consume large amounts of power.*
MIXING OF SOLIDS: EQUIPMENT- RIBBON BLENDER, KNEADER, DOUBLE CONE MIXER, TUMBLING MIXERS, DOUGH AND PASTE MIXERS

Mixing of Solids

A theory for solids mixing, as is the case generally for the processing of particulate solids, is not available as it is for liquids. However a number of mixing mechanisms can be identified and to a limited extent these can be related to mixing equipment. The solids mixing mechanisms which can be identified are diffusion, convection, and shear.

Particles diffuse under the influence of a concentration gradient in the same way that molecules diffuse. They move by inter-particle percolation, that is, in the void spaces between other particles under the influence of either gravity or, in higher speed mixers, of centrifugal effects. Fick's law can be used to describe this phenomenon.

Convection describes the movement of groups of particles from one place to another within the mixer volume because of the direct action of an impeller or a moving device within the mixer body. As in convection within fluids this is likely to be a more significant effect than diffusion but diffusional effects will still be present.

The shear mechanism operates when slipping planes are formed within the particulate mass, perhaps because of the action of a blade, which in turn allow particles to exploit new void spaces through which particles can then diffuse.

In addition to these mixing mechanisms, segregation acts against mixing to separate components which have different physical properties. Segregation is usually due to gravitational forces, but is heightened when centrifugal effects are present and occurs when particles have the possibility of falling through the spaces between other particles. The degree of segregation is a function of particle size (with smaller particles being more likely to segregate), density, and shape. Thus, larger size differences and larger density differences in a particulate mixture are likely to bring about increased segregation and make
mixing more difficult. It is more difficult to quantify the effect of shape, although gross differences in shape are more likely to lead to poor mixing.

**Equipment for Solids Mixing**

A huge variety of devices for the mixing of solids is available.

**Ribbon Blender**

The essential feature in these mixers is to displace parts of the mixture with respect to other parts. The ribbon blender, consists of a trough in which rotates a shaft with two open helical screws attached to it, one screw being right-handed and the other left-handed. As the shaft rotates sections of the powder move in opposite directions and so particles are vigorously displaced relative to each other.

It is usually operated in batch mode with mixer volumes up to about 15 m, but continuous operation is possible with feed rates up to 10 t/h. Helical ribbon mixers can be used for slightly cohesive solids, for very thin pastes or for the addition of liquids to solids. Mixing is strongly convective and segregation is far less pronounced than in either tumbling mixers or fluidised beds.

![Figure 9.1 Mixers (a) ribbon blender, (b) double-cone mixer](image1)

![Figure 9.2 Y-cone mixer](image2)
**Tumbling mixers / Cone Mixers:** Essentially these are enclosed containers which rotate about a horizontal axis and include the horizontal drum, double-cone, V-cone, Y-cone, and cube. The above figures show double-cone mixer and Y-cone mixer. These mixers are operated in batch mode being partially filled with solids (up to about 60% by volume). Tumbling mixers are run at a fraction of the critical speed required for centrifugation (at which all the solids would be thrown outwards towards the mixer walls) with a practical maximum speed of about 100 rpm. They are used for free-flowing solids, but small amounts of liquid may be added, and are best suited for particles of similar size and density because strong segregation can occur. Such mixers may have baffles fitted to the inner walls which help to lift solids or alternatively may be fitted with ploughs to assist convection.

**Dough and Paste Mixers**

Dough and pastes are mixed in machines that have, of necessity, to be heavy and powerful. Because of the large power requirements, it is particularly desirable that these machines mix with reasonable efficiency, as the power is dissipated in the form of heat, which may cause substantial heating of the product. Such machines may require jacketing of the mixer to remove as much heat as possible with cooling water.

Perhaps the most commonly used mixer for these very heavy materials is the kneader which employs two contra-rotating arms of special shape, which fold and shear the material across a cusp, or division, in the bottom of the mixer. The arms are of so-called sigmoid shape as indicated in below Figure 9.3.

![Figure 9.3 Kneader](image)

They rotate at differential speeds, often in the ratio of nearly 3:2. Developments of this machine include types with multiple sigmoid blades along
extended troughs, in which the blades are given a forward twist and the material makes its way continuously through the machine.

Another type of machine employs very heavy contra-rotating paddles, whilst a modern continuous mixer consists of an interrupted screw which oscillates with both rotary and reciprocating motion between pegs in an enclosing cylinder. The important principle in these machines is that the material has to be divided and folded and also displaced, so that fresh surfaces recombine as often as possible.
SIZE REDUCTION: INTRODUCTION, GRINDING AND CUTTING, ENERGY USED IN GRINDING, KICK’S LAW, RITTINGER’S LAW, BOND’S LAW

Size Reduction

Raw materials often occur in sizes that are too large to be used and, therefore, they must be reduced in size. Size reduction or ‘comminution’ is the unit operation in which the average size of solid pieces of food is reduced by the application of grinding, compression or impact forces. When applied to the reduction in size of globules of immiscible liquids (for example oil globules in water) size reduction is more frequently referred to as homogenization or emulsification. The size reduction of liquids to droplets is done by atomization. Size enlargement is achieved by extrusion, agglomeration or forming.

Size reduction has the following benefits in food processing:

• There is an increase in the surface-area-to-volume ratio of the food which increases the rate of drying, heating or cooling and improves the efficiency and rate of extraction of liquid components (for example fruit juice or cooking oil extraction).

• A similar range of particle sizes allows more complete mixing of ingredients (for example dried soup and cake mixes).

Size reduction and emulsification have little or no preservative effect. They are used to improve the eating quality or suitability of foods for further processing and to increase the range of products available. In some foods size reduction may promote degradation by the release of naturally occurring enzymes from damaged tissues, or by microbial activity and oxidation at the increased area of exposed surfaces, unless other preservative treatments are employed.

Different methods of size reduction are classified according to the size range of particles produced:

1. *Chopping, cutting, slicing and dicing*:
   (a) Large to medium
   (b) medium to small
   (c) small to granular

2. *Milling* to powders or pastes of increasing fineness

3. *Emulsification* and *homogenisation*
GRINDING AND CUTTING

**Grinding and cutting** reduce the size of solid materials by mechanical action, dividing them into smaller particles. Perhaps the most extensive application of grinding in the food industry is in the milling of grains to make flour, but it is used in many other processes, such as in the grinding of corn for manufacture of corn starch, the grinding of sugar and the milling of dried foods, such as vegetables.

**Cutting** is used to break down large pieces of food into smaller pieces suitable for further processing, such as in the preparation of meat for retail sales and in the preparation of processed meats and processed vegetables.

In the grinding process, materials are reduced in size by fracturing them. The mechanism of fracture is not fully understood, but in the process, the material is stressed by the action of mechanical moving parts in the grinding machine and initially the stress is absorbed internally by the material as strain energy. When the local strain energy exceeds a critical level, which is a function of the material, fracture occurs along lines of weakness and the stored energy is released. Some of the energy is taken up in the creation of new surface, but the greater part of it is dissipated as heat. Time also plays a part in the fracturing process and it appears that material will fracture at lower stress concentrations if these can be maintained for longer periods. Grinding is, therefore, achieved by mechanical stress followed by rupture and the energy required depends upon the hardness of the material and also upon the tendency of the material to crack - its friability.

The force applied may be compression, impact, or shear, and both the magnitude of the force and the time of application affect the extent of grinding achieved. For efficient grinding, the energy applied to the material should exceed, by as small a margin as possible, the minimum energy needed to rupture the material. Excess energy is lost as heat and this loss should be kept as low as practicable.

The important factors to be studied in the grinding process are the amount of energy used and the amount of new surface formed by grinding.
**Energy Used in Grinding**

Grinding is a very inefficient process and it is important to use energy as efficiently as possible. Unfortunately, it is not easy to calculate the minimum energy required for a given reduction process, but some theories have been advanced which are useful.

These theories depend upon the basic assumption that the energy required to produce a change $dL$ in a particle of a typical size dimension $L$ is a simple power function of $L$:

$$\frac{dE}{dL} = KL^n$$ (11.1)
where \( dE \) is the differential energy required, \( dL \) is the change in a typical dimension, \( L \) is the magnitude of a typical length dimension and \( K, n \) are constants.

**Kick** assumed that the energy required to reduce a material in size was directly proportional to the size reduction ratio \( dL/L \). This implies that \( n \) in eqn. (11.1) is equal to -1. If

\[ K = K_k f_c \]

where \( K_k \) is called Kick’s constant and \( f_c \) is called the crushing strength of the material, we have:

\[ \frac{dE}{dL} = K_k f_c L^{-1} \]

which, on integration gives:

\[ E = K_k f_c \log_e \left( \frac{L_1}{L_2} \right) \]  

(11.2) Equation

(2) is a statement of Kick’s Law. It implies that the specific energy required to crush a material, for example from 10 cm down to 5 cm, is the same as the energy required to crush the same material from 5 mm to 2.5 mm.

**Rittinger**, on the other hand, assumed that the energy required for size reduction is directly proportional, not to the change in length dimensions, but to the change in surface area. This leads to a value of -2 for \( n \) in eqn. (1) as area is proportional to length squared. If we put:

\[ K = K_R f_c \]

and so

\[ \frac{dE}{dL} = K_R f_c L^{-2} \]

where \( K_R \) is called Rittinger’s constant, and integrate the resulting form of eqn. (11.1), we obtain:

\[ E = K_R f_c \left( \frac{1/L_2}{1/L_1} \right) \]  

(11.3)
Equation (11.3) is known as Rittinger’s Law. As the specific surface of a particle, the surface area per unit mass, is proportional to $1/L$, eqn. (11.3) postulates that the energy required to reduce $L$ for a mass of particles from 10 cm to 5 cm would be the same as that required to reduce, for example, the same mass of 5 mm particles down to 4.7 mm. This is a very much smaller reduction, in terms of energy per unit mass for the smaller particles, than that predicted by Kick’s Law.

It has been found, experimentally, that for the grinding of coarse particles in which the increase in surface area per unit mass is relatively small, Kick’s Law is a reasonable approximation. For the size reduction of fine powders, on the other hand, in which large areas of new surface are being created, Rittinger’s Law fits the experimental data better.

Bond has suggested an intermediate course, in which he postulates that $n$ is $-\frac{3}{2}$ and this leads to:

\[ E = E_i \left( \frac{100}{L_2} \right)^{1/2} \left[ 1 - \left( \frac{1}{q^{1/2}} \right) \right] \quad (11.4) \]

Bond defines the quantity $E_i$ by this equation: $L$ is measured in microns in eqn. (11.4) and so $E_i$ is the amount of energy required to reduce unit mass of the material from an infinitely large particle size down to a particle size of 100 mm. It is expressed in terms of $q$, the reduction ratio where $q = L_1 / L_2$.

Note that all of these equations [eqns. (11.2), (11.3), and (11.4)] are dimensional equations and so if quoted values are to be used for the various constants, the dimensions must be expressed in appropriate units. In Bond’s equation, if $L$ is expressed in microns, this defines $E_i$ and Bond calls this the Work Index.

The greatest use of these equations is in making comparisons between power requirements for various degrees of reduction.

**EXAMPLE 1. Grinding of sugar**

Sugar is ground from crystals of which it is acceptable that 80% pass a 500 m sieve (US Standard Sieve No.35), down to a size in which it is acceptable that 80% passes a 88 m (No.170) sieve, and a 5-horsepower motor is found
just sufficient for the required throughput. If the requirements are changed such that the grinding is only down to 80% through a 125 m (No.120) sieve but the throughput is to be increased by 50% would the existing motor have sufficient power to operate the grinder? Assume Bond's equation.

Solution:

Using the subscripts 1 for the first condition and 2 for the second, and letting $m$ kg h$^{-1}$ be the initial throughput, then if $x$ is the required power

Now

$88 \ m = 8.8 \times 10^{-6} \ m \cdot 125 \ m = 125 \times 10^{-6} \ m \cdot 500 \ m = 500 \times 10^{-6} \ m$

$$E_1 = \frac{5}{m} = E_1[(100/88 \times 10^{-6})^{1/2} \ [1 - (88/500)^{1/2}]]$$

$$E_2 = \frac{x}{1.5m} = E_2[(100/125 \times 10^{-6})^{1/2} \ [1 - (125/500)^{1/2}]]$$

$$E_2/E_1 = \frac{x}{(1.5 \times 5)} = \frac{(88 \times 10^{-6})^{1/2} \ [1 - (125/500)^{1/2}]}{(125 \times 10^{-6})^{1/2} \ [1 - (88/500)^{1/2}]$$

$$\frac{x}{(7.5)} = 0.84 \times (0.500/0.58)$$

$$= 0.72$$

$$x = \text{5.4 horsepower}.$$ 

So the motor would be expected to have insufficient power to pass the 50% increased throughput, though it should be able to handle an increase of 40%.
SEPARATION BY CENTRIFUGATION AND FILTRATION

Foods are complex mixtures of compounds and the extraction or separation of food components is fundamental for the preparation of ingredients to be used in other processes (for example cooking oils from oilseeds or gelatin from connective tissue); or for retrieval of high value compounds, such as enzymes (e.g. papain from papaya for meat tenderisation or rennet from calf stomachs for cheese making) etc.

There are three main categories of separation:

1. Separation of liquids and solids from slurries, pastes, particulates or flours, where either one or both components may be valuable (for example juices, pectin, enzymes, cooking oil, cream and coffee solubles).
2. Separation of small amounts (less than 2%) of solids from liquids. Here the main purpose is purification of water or clarification of liquids such as wine, beer, juices, etc. and the solids are not valuable.
3. Extraction of small amounts of valuable materials using a solvent.

Centrifugation

There are two main applications of centrifugation: separation of immiscible liquids and separation of solids from liquids. Separation of solid particles from air by centrifugal action is done in the ‘cyclone’ separator.

Centrifugal force is generated when materials are rotated; the size of the force depends on the radius and speed of rotation and the density of the centrifuged material. In the separation of immiscible liquids, the denser liquid moves to the bowl wall and the lighter liquid is displaced to an inner annulus (Figure 13.1).
Fig. 13.1 Separation of immiscible liquids: \( r_1 \), radius of dense phase outlet; \( r_2 \), radius of light phase outlet; \( r_n \), radius of neutral zone.

The thickness of the layers is determined by the density of the liquids, the pressure difference across the layers and the speed of rotation. A boundary region between the liquids at a given centrifuge speed forms at a radius \( r_n \) where the hydrostatic pressure of the two layers is equal. This is termed the neutral zone and is important in equipment design to determine the position of feed and discharge pipes. It is found using:

\[
r^2 - A\frac{\rho_A}{\rho_B}B^2 = 0
\]

where \( \rho \) (kg/m\(^3\)) = density and \( r \) (m) = the radius. The subscripts A and B refer to the dense and light liquid layers respectively.

**Sample problem**

A bowl centrifuge is used to break an oil-in-water emulsion. Determine the radius of the neutral zone in order to position the feed pipe correctly. (Assume that the density of the continuous phase is 1000 kg/m\(^3\) and the density of the oil is 870 kg/m\(^3\). The outlet radii from the centrifuge are 3 cm and 4.5 cm.)

**Solution :**
Centrifuges are classified into three groups for:

1. separation of immiscible liquids
2. clarification of liquids by removal of small amounts of solids (centrifugal clarifiers)
3. removal of solids (desludging or dewatering centrifuges).

**Liquid–liquid centrifuges**

The simplest type of equipment is the *tubular bowl centrifuge*. It consists of a vertical cylinder (or bowl), typically 0.1 m in diameter and 0.75 m long, which rotates inside a stationary casing at between 15000 rev per min and 50 000 rev per min depending on the diameter. Feed liquor is introduced continuously at the base of the bowl and the two liquids are separated and discharged through a circular weir system into stationary outlets (Fig. 13.1).

**Disc bowl centrifuge**

Better separation is obtained by the thinner layers of liquid formed in the *disc bowl centrifuge* (Fig. 13.2). Here a cylindrical bowl, 0.2–1.2 m in diameter, contains a stack of inverted metal cones which have a fixed clearance of 0.5–1.27 mm and rotate at 2000–7000 rev/min. They have matching holes which form flow channels for liquid movement. Feed is introduced at the base of the disc stack and the denser fraction moves towards the wall of the bowl, along the underside of the discs. The lighter fraction is displaced towards the centre along the upper surfaces and both liquid streams are removed continuously by a weir system at the top of the centrifuge in a similar way to the tubular bowl system. Disc bowl centrifuges are used to separate cream from milk and to clarify oils, coffee extracts and juices. Disc bowl and tubular centrifuges have capacities of up to 150 000 l/h.
Filtration

Filtration is the removal of insoluble solids from a suspension (or ‘feed slurry’) by passing it through a porous material (or ‘filter medium’). The resulting liquor is termed the ‘filtrate’ and the separated solids are the ‘filter cake’. Filtration is used to clarify liquids by the removal of small amounts of solid particles (for example from wine, beer, oils and syrups).

When a suspension of particles is passed through a filter, the first particles become trapped in the filter medium and, as a result, reduce the area through which liquid can flow. This increases the resistance to fluid flow and a higher pressure difference is needed to maintain the flow rate of filtrate. The rate of filtration is expressed as follows:

\[
\text{Rate of filtration} = \frac{\text{driving force (the pressure difference across the filter)}}{\text{resistance to flow}}
\]

Assuming that the filter cake does not become compressed, the resistance to flow through the filter is found using

\[
R = \frac{V}{rAL}
\]

Where \( R \) (m\(^{-2}\)) = resistance to flow through the filter,

\( V \) (N s m\(^{-2}\)) = viscosity of the liquid,

\( r \) (m\(^{-2}\)) = specific resistance of the filter cake,
\[ V (\text{m}^3) = \text{volume of the filtrate,} \]
\[ V_c = \text{the fractional volume of filter cake in the feed liquid volume,} \]
\[ V_A (\text{m}^2) = \text{area of the filter and} \]
\[ L = \text{equivalent thickness of the filter and initial cake layer.} \]

**Equipment**

Gravity filtration is slow and finds little application in the food industry. Filtration equipment operates either by the application of pressure to the feed side of the filter bed or by the application of a partial vacuum to the opposite side of the filter bed. Filter aids are usually applied to the filter or mixed with the food to improve the formation of filter cake.

**Pressure filters**

Two commonly used pressure filters are the batch *plate-and-frame filter press* (Fig 13.3) and the *shell-and-leaf pressure filter*.

**Plate-and-frame filter press**

In the plate-and-frame design, cloth or paper filters are supported on vertical plates. Feed liquor is pumped into the press and liquid passes through the filter cloths and flows down the grooved surfaces of the plates to drain through an outlet channel in the base of each plate. A layer of cake builds up on the cloths until the space between the plates is filled. In operation, the pressure is increased to a pre-determined value and the plates are then back-washed with water. The press is dismantled and the cake is removed, ready to begin another cycle. The filter press has relatively low capital costs, high flexibility for different foods, it is reliable and easily maintained. It is widely used for the production of apple juice and cider. However, it is time consuming and highly labour intensive.

![Plate-and-frame filter press](image)

Fig. 13.3 Plate-and-frame filter press.
Expression

The main applications of expression are in the extraction of components plant materials either for direct consumption (for example fruit juices) or for use in subsequent processing (for example sugar, grape juice for wine and vegetable oils). These materials are located within the cell structure of the plants and it is necessary to disrupt the cells in order to release them. This is achieved either in a single-stage, which both ruptures the cells and expresses the liquid, or in two stages (size reduction to produce a pulp or flour, followed by separation in a press). In general the single-stage operation is more economical, permits higher throughputs and has lower capital and operating costs, but for some products that are especially hard (for example oil bearing nuts) a two-stage expression is more effective. Better extraction is achieved by heating oilseeds or flours to reduce the oil viscosity, release oil from intact cells and remove moisture. There is optimum moisture content for each type of oil seed to obtain a maximum yield of oil.

In fruit processing, the press should remove the maximum quantity of juice, without substantial quantities of solids, or phenolic compounds from the skins which cause bitterness and browning. This is achieved using lower pressures and fewer pressings. It is also necessary to increase the pressure slowly to avoid the formation of a dense impenetrable press cake, as the solid material is easily deformed and blocks the press.

The factors that influence the juice yield from a press include:

- maturity and growth conditions of the raw material
- extent of cell disruption
- thickness of the pressed solids and their resistance to deformation
- rate of increase in pressure, the time of pressing and the maximum pressure applied
- temperatures of solids and liquid and the viscosity of the expressed liquid.
Equipment

Batch presses

Common types of equipment for expressing juice or oils are the **tank press** and the **cage press**.

**Tank press**

The tank press is used for fruit juice production and consists of a horizontal cylinder which is divided internally by a membrane. During an automatically controlled pressing cycle of 1.5 h, fruit pulp is fed into one side of the membrane and compressed air is applied to the opposite side (Figure.14.1). Juice flows out through channels and, when pressing is completed, the tank is rotated to loosen and discharge the press residue. High yields of good-quality juice are obtained by the gentle increase in pressure at capacities ranging from 3600 kg to 25 000 kg.

In the cage press, up to 2 t of fruit pulp or oilseed flour is placed into a vertical perforated or slatted cage, either loose or in cloth bags depending on the nature of the material. In larger presses, ribbed layer plates are used to reduce the thickness of the pulp or flour bed. The pressure is gradually increased on the top plate by an hydraulic system or motor-driven screw thread and liquid is collected at the base of the press. The equipment allows close control over the pressure exerted on the pulp/flour and may operate semi-automatically to reduce labour costs.

![Diagram of tank press](image)

Figure 14.2 Tank press: 1, tank filled; 2, membrane partly inflated; 3, membrane further inflated; 4, loosening residue; 5, discharge.
Continuous presses

There are several types of continuous press used commercially: the belt press for fruit processing, the screw expeller for both fruit processing and oil extraction, and the roller press for sugar cane processing.

Screw expeller

The screw expeller consists of a robust horizontal barrel containing a stainless steel helical screw (Figure 14.4). The pitch of the screw flights gradually decreases towards the discharge end, to increase the pressure on the material as it is carried through the barrel. The final section of the barrel is perforated to allow expressed liquid to escape. Press cake is discharged through the barrel outlet and the pressure in the barrel is regulated by adjusting the diameter of the discharge port. Frictional heat reduces the viscosity of the oil and some types of expellers have supplementary heaters fitted to the barrel to improve yields. In juice extraction the barrel is cooled to reduce the friction heat, generated by the movement of food, which may have an undesirable effect on flavour and aroma. Capacities range from 40 kg/h to 8000 kg/ h. The oil cake has 5–18% (w/w) residual oil, depending on the type of oil-seed and the operating conditions.
**Extraction using solvents**

Unit operations that involve separation of specific components of foods are important in a number of applications, including production of:

- cooking oils or specialty oils from nuts and seeds
- flavors and essential oils (e.g. black pepper, cardamom, clove, ginger, hops, parsley, vanilla, etc.)
- coffee
- sugar
- removal of caffeine from coffee and tea.

Once the solvent has been removed from the extracted foods, some may be used directly (for example cooking oils) or they may be further processed by concentration and/or dehydration.

The main types of solvents used for extraction are water, organic solvents or supercritical carbon dioxide.

Solid-liquid extraction involves the removal of a desired component (the solute) from a food using a liquid (the solvent) which is able to dissolve the solute. This involves mixing the food and solvent together, either in a single stage or in multiple stages, holding for a pre-determined time and then separating the solvent. During the holding period there is mass transfer of solutes from the food material to the solvent, which occurs in three stages:

1. the solute dissolves in the solvent
2. the solution moves through the particle of food to its surface
3. the solution becomes dispersed in the bulk of the solvent.

During extraction, the holding time should therefore be sufficient for the solvent to dissolve sufficient solute and for the changes in composition to approach an equilibrium. The time required depends on the solubility of a given solute in the solvent selected and also on the following factors:

- **The temperature of extraction**: Higher temperatures increase both the rate at which solutes dissolve in the solvent and the rate of diffusion into the bulk of the solvent. The temperature of most extraction operations is limited to less than 100ºC by economic considerations, extraction of undesirable components at higher temperatures or heat damage to food components.

- **The surface area of solids exposed to the solvent**: The rate of mass transfer is directly proportional to the surface area, so reductions in particle size
(giving an increase in surface area) increase the rate of extraction up to certain limits.

- **The viscosity of the solvent.** This should be sufficiently low to enable the solvent to penetrate easily the bed of solid particles.

- **The flow rate of the solvent.** Higher flow rates reduce the boundary layer of concentrated solute at the surface of particles and thus increase the rate of extraction.

Table 14.1: Solvents used to extract food components

<table>
<thead>
<tr>
<th>Food</th>
<th>Solvent</th>
<th>Final solute concentration (%)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decaffeinated coffee</td>
<td>Supercritical carbon dioxide, water or</td>
<td>N/A</td>
<td>30–50 (CO₂)</td>
</tr>
<tr>
<td></td>
<td>methylene chloride</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish livers, meat byproducts</td>
<td>Acetone or ethyl ether</td>
<td>N/A</td>
<td>30–50</td>
</tr>
<tr>
<td>Hop extract</td>
<td>Supercritical carbon dioxide</td>
<td>N/A</td>
<td>&lt;100–180</td>
</tr>
<tr>
<td>Instant coffee</td>
<td>Water</td>
<td>25–30</td>
<td>70–90</td>
</tr>
<tr>
<td>Instant tea</td>
<td>Water</td>
<td>2.5–5</td>
<td>N/A</td>
</tr>
<tr>
<td>Olive oil</td>
<td>Carbon disulphide</td>
<td>N/A</td>
<td>63–70 (hexane)</td>
</tr>
<tr>
<td>Seed, bean and nut oils</td>
<td>Hexane, heptane or cyclohexane</td>
<td>N/A</td>
<td>90–99 (heptane)</td>
</tr>
<tr>
<td>(e.g. from soybeans, groundnuts, cottonseed, sunflower seed, etc.)</td>
<td></td>
<td></td>
<td>71–85 (cyclohexane)</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>Water</td>
<td>approx. 15</td>
<td>55–85</td>
</tr>
</tbody>
</table>

Adapted from data of Brennan et al. (1990) and Clarke (1990).
MEMBRANE CONCENTRATION (HYPERFILTRATION AND ULTRAFILTRATION)

Reverse osmosis (RO) (or ‘hyperfiltration’) and ultrafiltration (UF) are both unit operations in which water and some solutes in a solution are selectively removed through a semi-permeable membrane. They are similar in that the driving force for transport across the membrane is the pressure applied to the feed liquid. However, reverse osmosis is used to separate water from low-molecular-weight solutes (for example salts, mono-saccharides and aroma compounds), which have a high osmotic pressure. A high pressure, five to ten times that used in UF (4000–8000X 10³ Pa), is therefore necessary to overcome this (hence the term reverse osmosis).

The largest commercial food application of reverse osmosis is the concentration of whey from cheese manufacture, either as a pre-concentration stage prior to drying or for use in the manufacture of ice cream. Reverse osmosis is also used to:

- concentrate and purify fruit juices (Robe, 1983), enzymes, fermentation liquors and vegetable oils
- to concentrate wheat starch, citric acid, egg white, milk, coffee, syrups, natural extracts and flavors
- to clarify wine and beer
- to demineralise and purify water from boreholes or rivers or by desalination of sea water.

In the last application, monovalent and polyvalent ions, particles, bacteria and organic materials with a molecular weight greater than 300 are all removed by up to 99.9% to give high-purity process water for beverage manufacture and other applications.

Other applications include ‘dealcoholisation’ to produce low-alcohol beers, cider and wines, and recovery of proteins or other solids from distillation residues, dilute juices, waste water from corn milling or other process wash waters. Membrane pre-concentration is also used to prepare coffee extracts and liquid egg for drying and to pre-concentrate juices and dairy products before evaporation, so improving the economy of evaporators. Concentrating fluids by removal of water at low temperatures in the dairy, fruit juice and sugar
processing industries competes with vacuum evaporation and freeze concentration. The advantages of membrane concentration over concentration by evaporation are:

- the food is not heated, and there is therefore negligible loss of volatiles or changes to nutritional or eating quality
- in contrast with boiling, membrane concentration does not involve a change in phase and therefore uses energy more efficiently (Table 6.4)
- simple installation with lower labour and operating costs
- no requirement for steam boilers.

The main limitations of membrane concentration are:

- variation in the product flow rate when changes occur in the concentration of feed liquor
- higher capital costs than evaporation
- a maximum concentration to 30% total solids
- fouling of the membranes (deposition of polymers), which reduces the operating time between membrane cleaning.

Different types of membrane reject solutes with specific ranges of molecular weight. These molecular weight ‘cut-off’ points are used to characterize membranes.

For reverse osmosis membranes, the cut-off points range from molecular weights of 100 Da at 4000–7000 X10³ Pa to 500 Da at 2500–4000 X10³ Pa.

![Size separation capabilities of different membrane systems.](image-url)
The term *nanofiltration* (NF) (or ‘loose reverse osmosis’) is used when membranes remove materials having molecular weights in the order of 300–1000 Da (Rosenberg, 1995). This compares to a molecular weight range of 2000–300 000 for ultrafiltration membranes, although above 30 000 there is overlap with microfiltration (Fig. 15.2). NF is capable of removing ions that contribute significantly to the osmotic pressure and thus allows operation at pressures that are lower than those needed for RO.
EVAPORATION, BOILING POINT ELEVATION, TYPES OF
EVAPORATORS, BATCH TYPE PAN EVAPORATOR, NATURAL
CIRCULATION EVAPORATORS

Evaporation
Evaporation is an important unit operation commonly employed to remove water from dilute liquid foods to obtain concentrated liquid products. Removal of water from foods provides microbiological stability and assists in reducing transportation and storage costs. A typical example of the evaporation process is in the manufacture of tomato paste, usually around 35-37% total solids obtained by evaporating water from tomato juice, which has an initial concentration of 5-6%
total solids.

Evaporation differs from dehydration, since the final product of the evaporation process remains in liquid state. It also differs from distillation, since the vapors produced in the evaporator are not further divided into fractions. In Fig. 25.1 a simplified schematic of an evaporator is shown.

Fig. 25.1 Single effect evaporator

Essentially, an evaporator consists of a heat exchanger enclosed in a large chamber; a non contact heat exchanger provides the means to transfer heat from low-pressure steam to the product. The product inside the evaporation chamber is kept under vacuum. The presence of vacuum causes the temperature difference between steam and product to increase and the product boils at relatively low temperatures, thus minimizing heat damage. The vapors produced are conveyed
through a condenser to a vacuum system. The steam condenses inside the heat exchanger and the condensate is discarded.

In the evaporator shown in Fig. 25.1, the vapors produced are discarded without further utilizing their inherent heat, therefore this type of evaporator is called a **single-effect evaporator**, since the vapors produced are discarded. If the vapors are reused as the heating medium in another evaporator chamber, as shown in Fig. 25.2, the evaporator system is called a **multiple-effect evaporator**.

![Evaporator Diagram](image)

**Fig. 25.2 Multiple (triple)-effect evaporator**

In a multi-effect evaporator, steam is used only in the first effect. The use of vapors as a heating medium in additional effects results in obtaining higher energy-use efficiency from the system. The partially concentrated product leaving the first effect is introduced as feed into the second effect. After additional concentration, product from the second effect becomes feed for the third effect. The product from the third effect leaves at the desired concentration. This particular arrangement is called a **forward feed system**. Other flow arrangements used in industrial practice include **backward feed systems** and **parallel feed systems**.

The characteristics of the liquid food have a profound effect on the performance of the evaporation process. As water is removed the liquid becomes increasingly concentrated, resulting in reduced heat transfer. The boiling point rises as the liquid concentrates resulting in a smaller differential of temperature between the heating medium and the product. This causes reduced rate of heat transfer.

Food products are noted for their heat sensitivity. Evaporation processes must involve reducing the temperature for boiling as well as the time of heating, to avoid excessive product degradation.
**Boiling-Point Elevation**

Boiling-point elevation of a solution (liquid food) is defined as the increase in boiling point over that of pure water, at a given pressure.

![Graph showing boiling point elevation](image)

Fig. 25.3 Duhring lines illustrating the influence of solute concentration on boiling point elevation

A simple method to estimate boiling-point elevation is the use of Duhring’s rule. The Duhring rule states that a linear relationship exists between the boiling-point temperature of the solution and the boiling-point temperature of water at the same pressure. Duhring lines for a sodium chloride-water system are shown in Fig.25.3.

**Types of Evaporators**

Several types of evaporators are used in the food industry.

1. **Batch-Type Pan Evaporator**

One of the simplest types of evaporators used in the food industry is the batch-type pan evaporator, shown in Fig.25.4. The product is heated in a steam jacketed spherical vessel. The heating vessel may be open to the atmosphere or connected to a condenser and vacuum. Vacuum permits boiling the product at temperatures lower than the boiling point at atmospheric pressure, thus reducing the thermal damage to heat sensitive products.
Fig. 25.4 A batch-type pan evaporator

The heat-transfer area per unit volume in a pan evaporator is small. Thus, the residence time of the product is usually very long. Heating of the product occurs mainly due to natural convection, resulting in smaller convective heat transfer coefficients. The poor heat transfer characteristics substantially reduce the processing capacities of the batch-type pan evaporators.

2. Natural Circulation Evaporators

In natural circulation evaporators, short vertical tubes, typically 1-2 m long and 50-100 mm in diameter, are arranged inside the steam chest. The whole calandria (tubes and steam chest) is located in the bottom of the vessel. The product, when heated, rises through these tubes by natural circulation while steam condenses outside the tubes. Evaporation takes place inside the tubes, and the product is concentrated. The concentrated liquid falls back to the base of the vessel through a central annular section. A natural circulation evaporator is shown in Fig. 25.5.

Fig. 25.5 A natural circulation evaporator
1. Rising-Film Evaporator

In a rising-film evaporator (Fig. 26.1), a low-viscosity liquid food is allowed to boil inside 10-15 m long vertical tubes. The tubes are heated from the outside with steam. The liquid rises inside these tubes by vapors formed near the bottom of the heating tubes. The upward movement of vapors causes a thin liquid film to move rapidly upward. A temperature differential of at least 14°C between the product and the heating medium is necessary to obtain a well developed film. High convective heat-transfer coefficients are achieved in these evaporators. Liquid can be recirculated if necessary to obtain the required solid concentration.

![Diagram of Rising-Film Evaporator](Image)

**Fig. 26.1** A rising-film evaporator

2 Falling-Film Evaporator

In contrast to the rising-film evaporator, the falling-film evaporator has a thin liquid film moving downward under gravity on the inside of the vertical tubes. (Fig.26.2). The design of such evaporators is complicated by the fact that distribution of liquid in a uniform film flowing downward in a tube is more difficult to obtain than an upward flow system such as in a rising-film evaporator. This is accomplished by the use of specially designed distributors or spray nozzles.
The falling-film evaporator allows a greater number of effects than the rising-film evaporator. For example, if steam is available at 110 °C and the boiling temperature in the last effect is 50°C, then the total available temperature differential is 60°C. Since rising-film evaporators require 14°C temperature differential across the heating surface, only four effects are feasible. However, as many as 10 or more effects may be possible using a falling-film evaporator. The falling-film evaporator can handle more viscous liquids than the rising-film type. This type of evaporator is best suited for highly heat-sensitive products such as orange juice. Typical residence time in a falling-film evaporator is 20-30 seconds, compared with a residence time of 3-4 minutes in a rising-film evaporator.

3. Rising/Falling-Film Evaporator

In the rising/falling-film evaporator the product is concentrated by circulation through a rising-film section followed by a falling-film section of the evaporator. As shown in Fig.26.3, the product is first concentrated as it ascends through a rising tube section, followed by the pre-concentrated product descending through a falling-film section; there it attains its final concentration.

4 Forced-Circulation Evaporator

The forced-circulation evaporator involves a non-contact heat exchanger where liquid food is circulated at high rates (Fig. 26.4). A hydrostatic head, above the top of the tubes, eliminates any boiling of the liquid. Inside the separator, absolute pressure is kept slightly lower than that in the tube bundle. Thus, the liquid entering
the separator flashes to form a vapor. The temperature difference across the heating surface in the heat exchanger is usually 3-5°C. **Axial flow pumps** are generally used to **maintain high circulation rates** with **linear velocities of 2-6 m/s**, compared with a linear velocity of **0.3-1 m/s** in **natural-circulation evaporators**. Both capital and operating costs of these evaporators are very low in comparison with other types of evaporators.

Fig. 26.4 A forced-circulation evaporator

5. **Plate evaporators**

In addition to the tubular shape, **plate evaporators** are also used in the industry. Plate evaporators use the principles of rising falling-film, falling-film, wiped-film, and forced-circulation evaporators. The plate configuration often provides features that make it more acceptable.

A **rising/falling-film plate** evaporator is more compact, thus requiring less floor area than a tubular unit.
DESIGN OF A SINGLE EFFECT EVAPORATOR, MATERIAL AND
ENERGY BALANCES, EVAPORATOR EFFICIENCY, BOILING POINT
ELEVATION, METHODS OF IMPROVING EVAPORATOR EFFICIENCY

Design of a Single Effect Evaporator

The primary quantities required to design an evaporator are the flow rates of the major streams: feed, vapour and concentrated liquor; the steam flow rate and the area of the heat transfer surface across which heat is transferred from steam to liquid in the evaporator. This requires a material balance, an enthalpy balance and a heat transfer rate equation to be solved simultaneously.

![Diagram of single effect evaporator](image)

**Fig. 27.1 Single effect evaporator: Material and energy balance**

**Material and Energy Balances**

Referring to Figure 27.1, an overall material balance across a single effect evaporator yields

\[ F = V + L \]  \hspace{1cm} (27.1)

where \( F \), \( V \), and \( L \) are the mass flow rates of feed, vapour, and liquor, respectively.

The component material balance is now

\[ x_F F + y V + x_L L \]  \hspace{1cm} (27.2)

where \( x_F \), \( y \), and \( x_L \) are the mass fractions of solids in the feed, vapour and liquor, respectively. However, because there is no solids in the vapour stream, \( y = 0 \) and the component balance reduces to

\[ x_F F + x_L L \]  \hspace{1cm} (27.3)

An enthalpy balance over the evaporator involves two further streams, the **inlet steam** \( S \) and the **condensate** \( C \). The combined enthalpy of the feed and
the steam must balance that of the vapour, liquor and condensate. Thus, if \( h_F \) is the specific enthalpy of the feed, \( h_S \) that of the steam and so on,

\[
F h_F S h_s V h_v L h_L S h_c
\]  \[\text{(27.4)}\]

where each term in Equation (4) represents a flow of heat associated with that particular stream and has units of either W or kW if \( h \) has units of J.kg\(^{-1}\) or kJ.kg\(^{-1}\), respectively. Strictly, the steam and condensate should be included in the material balances. However they may be omitted because, of course, the flow rate and composition of the steam remains unchanged as it gives up heat and condenses. Thus, in Equation (12.4), \( S = C \). For the purpose of calculation, the enthalpies of liquid streams are obtained from steam tables and care must be taken not to confuse the subscripts \( F \) and \( f \).

Rearranging Equation (27.4) to give the steam flow rate produces

\[
S (h_s, h_c) = V h_v L h_L F h_F
\]  \[\text{(27.5)}\]

![Diagram of Single effect evaporator: material and enthalpy balance](image)

Fig.27.2 Single effect evaporator: material and enthalpy balance

Now the left-hand side of Equation (27.5), the difference between the enthalpy of the steam and that of the condensate, must be equal to the rate \( Q \) at which heat is transferred from the steam to the feed, that is,

\[
Q = S(h_s, h_c)
\]  \[\text{(27.6)}\]

The enthalpy given up by the steam is transferred across the tube walls of the calandria, across which the temperature difference is \( T \), and therefore

\[
S(h_s, h_c) U A T
\]  \[\text{(27.7)}\]
where \( A \) is the heat transfer surface area; this area must be determined in order for the calandria and the evaporator to be sized. An evaporator of course is a kind of heat exchanger and the overall heat transfer coefficient can be obtained by summing the various thermal resistances as in the examples of chapter seven. The temperature driving force is that between the steam and the boiling liquor in the evaporator. Hence

\[
T - T_s - T_e = (27.8)
\]

Any evaporator problem now requires the simultaneous solution of Equations (27.3), (27.5), and (27.7). However it is very likely that there will be sufficient information available to solve the material balance independently. Equally, if the working pressures of the evaporator are specified then the steam and condensate enthalpies can be determined from steam tables. The major difficulty may be in finding values of enthalpy and boiling point for food solutions, but a reasonable first estimate is to assume that the properties of food solutions approximate to those of water.

**Example 27.1**

A single effect evaporator is to be used to concentrate a food solution containing 15% (by mass) dissolved solids to 50% solids. The feed stream enters the evaporator at 291 K with a feed rate of 1.0 kg s\(^{-1}\). Steam is available at a pressure of 2.4 bar and an absolute pressure of 0.07 bar is maintained in the evaporator. Assuming that the properties of the solution are the same as those of water, and taking the overall heat transfer coefficient to be 2,300 W m\(^{-2}\) K\(^{-1}\), calculate the rate of steam consumption and the necessary heat transfer surface area.

Working in units of kg s\(^{-1}\), the overall material balance becomes

\[
1.0 = v L
\]

Substituting into the component material balance for \( x_f = 0.15 \) and \( x_L = 0.50 \) gives
from which the unknown liquor flow rate is

\[ L = 0.3 \text{ kg s}^{-1} \]

Hence from the overall balance the flow rate of vapour is

\[ V = 0.7 \text{ kg s}^{-1} \]

To proceed with an enthalpy balance, specific enthalpies must be obtained from steam tables. If the steam and condensate remain saturated at 2.40 bar then

\( h_s \) is equal to \( h_g \)

at 2.40 bar and \( h_c \) is equal to \( h_f \) at 2.40 bar. Thus

\[ h_s = 2,715 \text{ kJ kg}^{-1} \text{ and } h_c = 530 \text{ kJ kg}^{-1}. \]

The feed enthalpy is determined by its temperature. Assuming the feed to be pure water, \( h_f \) is equal to \( h_f \) at 291 K and therefore \( h_f \) is 75.5 kJ kg\(^{-1}\). The enthalpies of the vapour and liquor streams are a function of the pressure within the evaporator: \( h_V = 2,572 \text{ kJ kg}^{-1} \) \( (h_g \text{ at } 0.07 \text{ bar}) \) and \( h_L = 163 \text{ kJ kg}^{-1} \) \( (h_f \text{ at } 0.07 \text{ bar}) \). The enthalpy balance [Equation (5)] now becomes

\[ S (2715 - 530) = (0.70 \times 2572) + (0.30 \times 163) - (1.0 \times 75.5) \]

from which \( S = 0.812 \text{ kgs}^{-1} \). The rate of heat transfer, from Equation (6), is now

\[ Q = 0.812 (2715 - 530) \text{ kW or } Q = 1774 \text{ kW} \]

The temperature of steam at 2.4 bar is \( T_s = 126.1 \text{ °C} \) and the temperature of saturated liquid water at the evaporator pressure of 0.07 bar is \( T_E = 39.0 \text{ °C} \). Thus to find the heat transfer area from the rate equation,

\[ A \frac{Q}{U(T_s, T_E)} \quad A \frac{1774}{2.30 (126.1 - 39.0)} \]

or

\[ A = 8.86 \text{ m}^2 \]

**Evaporator Efficiency**

A common measure of the efficiency of an evaporator is the mass of vapour generated per unit mass of steam admitted to the calandria. This quantity is known as the economy. Thus

\[ economy = \frac{V}{S} \quad -----(27.9) \]
Clearly it is impossible, in a single effect evaporator, for 1 kg of steam to generate more than 1 kg of vapour. In practice, because of energy losses, the economy will be below unity and values of 0.8 or slightly greater may be expected for industrial units.

**Example 27.2**

An aqueous food solution at a temperature of 18 °C contains 6% solids by mass and is to be concentrated to 24 % solids in a single effect evaporator. The evaporator has a total heat transfer surface area of 30 m², uses steam at 300 kPa and operates under a vacuum of 79.3 kPa. Previous operating experience with these conditions suggests an overall heat transfer coefficient of 2,200 W m⁻²K⁻¹. Determine the mass flow rate of steam required and the evaporator economy.

The various specific enthalpies and temperatures are obtained from steam tables as follows:

For the steam and condensate at 300 kPa, \( h_s = 2,725 \text{ kJ kg}^{-1}, \ h_c = 561 \text{ kJ kg}^{-1} \) and the steam temperature is 133.5 °C. The enthalpy of feed at a temperature of 18 °C is \( h_F = 75.5 \text{ kJ kg}^{-1} \). Taking atmospheric pressure to be 101.3 kPa, the pressure within the evaporator is 22.0 kPa and therefore the evaporator temperature (assuming no boiling point elevation) is 62.2 °C. Consequently \( h_v = 2,613 \text{ kJ kg}^{-1} (h_g \text{ at 0.22 bar}) \) and \( h_L = 260 \text{ kJ kg}^{-1} (h_f \text{ at 0.22 bar}) \).

From Equation (7) the steam flow rate is

\[
S = \frac{U A T_c (h_s - h_c)}{h_s - h_c} = \frac{2.20 \times 30 \times (133.5 - 62.2)}{2,725 - 561}
\]

or

\[
S = 2.175 \text{ kg s}^{-1}
\]

Because neither the feed flow rate nor the product flow rate is specified, the material and energy balances must be solved simultaneously. The component balance, with \( X_F = 0.06 \) and \( X_L = 0.24 \), is

\[0.06 F = 0.24 L\]

from which

\[F = 4L\]
Substituting this into the enthalpy balance gives

\[ S(h_s h_v) (4L L) h_v L h_L 4L h_f \]

And

\[ 2.175(2725 - 561) = (3L \times 2613) + 260 L - 302 L \]

This can be solved to give \( L = 0.604 \text{ kg s}^{-1} \) and from the overall material balance therefore \( V = 1.811 \text{ kg s}^{-1} \). Consequently the economy becomes

\[ \text{economy} = \frac{1.811}{2.175} \text{ economy} = 0.833 \]
Boiling Point Elevation

The vapour pressure of an aqueous solution is less than that of pure water. Consequently the boiling point of the solution is higher than that of pure water and this difference must be taken into account in the enthalpy balance. The boiling point rise or boiling point elevation is defined as the difference between the boiling point of the solution and that of pure water, at the same pressure.

METHODS OF IMPROVING EVAPORATOR EFFICIENCY

In single stage evaporation the enthalpy of the vapour is wasted because the vapour is either vented to atmosphere or condensed. This poor use of steam results in low thermal efficiency and a low steam economy. Reusing the vapour, either by recycling it to the calandria or by passing it to the calandria of a second evaporator, means that 1 kg of original steam can be used to generate more than 1 kg of vapour giving economies greater than unity.

Vapour Recompression

(a) Mechanical recompression Mechanical recompression (Figure 27.3(a)) of the exhaust vapour from an evaporator allows the enthalpy of the vapour to be reused. In compressing the vapour its enthalpy is increased to that of the original steam. Because of inevitable heat losses in the system some make-up steam will be required but a large increase in economy can be expected. A major disadvantage of this technique is that a large volume of vapour must be handled which in turn requires a large compressor; positive displacement compressors are normally used. The increase in steam economy must be balanced against the running costs of the compressor.

(b) Steam jet ejector: An alternative method of reusing the vapour is to inject high pressure steam via a nozzle, or steam jet ejector (Figure 27.3 (b)). This creates a vacuum which entrains the low pressure vapour from the evaporator at right angles. The combined stream is then recycled to the calandria. Again, the fresh steam requirement is reduced but there are several advantages over mechanical recompression. The steam jet ejector has the ability to handle very large volumes of vapour and can operate at lower pressures. There are no moving parts, no power requirement and corrosion resistant materials can easily be used. The major disadvantage is that optimum operation of such a device occurs at a
specific pressure and temperature; variation of the conditions in the evaporator may well lead to a reduction in the economy which can be achieved.

Fig. 27.3(a) Mechanical Vapor recompression

Fig. 27.3(b) Steam ejector vapor recompression
SIZING OF MULTIPLE EFFECT EVAPORATORS

The rate equation can be written for each effect in turn

\[ Q_1 U_1 A_1 T_1 \]
\[ Q_2 U_2 A_2 T_2 \]
\[ Q_3 U_3 A_3 T_3 \]

(28.1)

where the temperature differences are defined by

\[ T_1 T_1 \]
\[ T_2 T_2 \]
\[ T_3 T_3 \]

(28.2)

and the subscripts 1, 2, and 3 refer to the first, second and third effects, respectively.

If now it is assumed that there is no boiling point rise, that the enthalpy required to raise the feed to the temperature \( T_1 \) can be neglected and that the enthalpy carried by the concentrated liquor to subsequent effects is negligible, then the heat flux \( Q_1 \) appears as the latent heat of the vapour in the calandria of effect 2. Therefore

\[ Q_1 Q_2 Q_3 \]

(28.3)

and

\[ U_1 A_1 T_1 U_2 A_2 T_2 U_3 A_3 T_3 \]

(28.4)

If each unit is geometrically similar each will have the same area and

\[ U_1 T_1 U_2 T_2 U_3 T_3 \]

(28.5)

The total capacity of the evaporator \( Q \) is then given by

\[ Q Q_1 Q_2 Q_3 \]

(28.6)

and

\[ Q U_{av} A(T_1 T_2 T_3) \]

(28.7)
where $A$ is the area of a single effect and $U_{av}$ is an average overall heat transfer coefficient.

It is important to understand that a single effect evaporator will have approximately the same capacity $Q$ as the multiple effect evaporator if the temperature difference is the same as the total temperature difference of the multiple effect unit, the area is the same as the area of one effect and the overall heat transfer coefficient is the same. The advantage of multiple effect evaporation is not an increased capacity but an increased steam economy. In an $n$ effect evaporator $1$ kg of steam evaporates approximately $n$ kg of vapour. Thus the economy of the multiple effect system is greater but the capital cost is greatly increased. For $n$ effects the capital cost will be approximately $n$ times that of a single effect and the optimum number of effects is a balance between the capital cost on the one hand and the improved economy and therefore lower operating costs on the other.

In order to determine the area of a multiple effect evaporator an iterative calculation is required. If the likely values of the overall heat transfer coefficient for each effect are known then, together with the temperature in the final effect (which is a function of the degree of vacuum applied), a first approximation of the temperature differences $T_1, T_2$ and $T_3$ can be obtained from Equation (28.4). This will give the temperature in each effect from which the enthalpies of vaporization can be found and hence the material and energy balances can be solved to give the steam and vapour flow rates. A first approximation of the area of each effect can now be made from the rate equations [Equation (27.9)]. Because of the assumptions made in this procedure, it is very likely that this first iteration will give unequal areas. A new approximation of each temperature difference is now obtained from an equation of the form

$$newT = \frac{T_1 A}{A_{mean}}$$

(28.8)

where $A_{mean}$ is the average of each effect area. This calculation is repeated until the areas of each effect are sufficiently close together.
TRAY AND CABINET DRYER, TUNNEL DRYER, PUFF-DRYING, FLUIDIZED - BED DRYING, SPRAY DRYING, FREEZE - DRYING

Tray or Cabinet Dryers

These types of dryers use trays or similar product holders to expose the product to heated air in an enclosed space. The trays holding the product inside a cabinet or similar enclosure (Fig.30.1) are exposed to heated air so that dehydration will proceed. Air movement over the product surface is at relatively high velocities to ensure that heat and mass transfer will proceed in an efficient manner.

![Fig.30.1 Cabinet Type Tray Drier](image)

In most cases, cabinet dryers are operated as batch systems and have the disadvantage of non-uniform drying of a product at different locations within the system. Normally, the product trays must be rotated to improve uniformity of drying.

Tunnel Dryers

Figures 30.2(a) and 30.2(b) show examples of tunnel dryers. As illustrated, the heated drying air is introduced at one end of the tunnel and moves at an established velocity through trays of products being carried on trucks. The product trucks are moved through the tunnel at a rate required to maintain the residence time needed for dehydration. The product can be moved in the same direction as the air flow to provide concurrent dehydration with the product moving in the direction opposite to air flow. The arrangement used will depend on the product and the sensitivity of quality characteristics to temperature.
With concurrent systems, a high-moisture product is exposed to high temperature air, and evaporation assists in maintaining lower product temperature. At locations near the tunnel exit, the lower-moisture product is exposed to lower-temperature air. In counter current systems, a lower-moisture product is exposed to high-temperature air, and a smaller temperature gradient exists near the product entrance to the tunnel.

![Diagram of concurrent flow tunnel dryer](image1)

**Fig. 30.2(a) A concurrent flow tunnel dryer**

![Diagram of counter current flow tunnel dryer](image2)

**Fig. 30.2(b) A counter current flow tunnel dryer**

**Puff-Drying**

In this drying process foods are dried by explosion puff-drying. This process is accomplished by exposing a relatively small piece of product to high pressure and high temperature for a short time, after which the product is moved to atmospheric pressure. This results in flash evaporation of water and allows vapors from the interior parts of the product to escape. Products produced by puff-drying have very high porosity with rapid rehydration characteristics. Puff-drying is particularly effective for products with significant falling-rate drying periods. The rapid
moisture evaporation and resulting product porosity contribute to rapid moisture removal during the final stages of drying. The puff-drying process is accomplished most efficiently by using 2 cm cube shapes. These pieces will dry rapidly and uniformly and will rehydrate within 15 minutes.

**Fluidized-Bed Drying**

In this system, the product pieces are suspended in the heated air throughout the time required for drying. As illustrated in Figure 30.3, the movement of product through the system is enhanced by the change in mass of individual particles as moisture is evaporated. The movement of the product created by fluidized particles results in equal drying from all product surfaces. The primary limitation to the fluidized-bed process is the size of particles that will allow efficient drying. As would be expected, smaller particles can be maintained in suspension with lower air velocities and will dry more rapidly. Not all products can be adapted dried with this process.

![Fluidized bed drier](image)

**Fig.30.3 Fluidized bed drier**

**Spray Drying**

The drying of liquid food products is often accomplished in a spray dryer. Moisture removal from a liquid food occurs after the liquid is atomized or sprayed into heated air within a drying chamber. Although various configurations of the chamber are used, the arrangement shown in Figure 30.4 illustrates the introduction of liquid droplets into a heated air stream.
While liquid food droplets are moving with the heated air, the water evaporates and is carried away by the air. Much of the drying occurs during a constant-rate period and is limited by mass transfer at the droplet surface. After reaching the critical moisture content, the dry food particle structure influences the falling-rate drying period. During this portion of the process, moisture diffusion within the particle becomes the rate-limiting parameter.

![Spray drying System](image)

**Fig.30.4 Spray drying System**

After the dry food particles leave the drying chamber, the product is separated from air in a cyclone separator. The dried product is then placed in a sealed container at moisture contents that are usually below 5%. Product quality is considered excellent due to the protection of product solids by evaporative cooling in the spray dryer. The small particle size of dried solids promotes easy reconstitution when mixed with water.

**Freeze-Drying**

Freeze-drying is accomplished by reducing the product temperature so that most of the product moisture is in a solid state, and by decreasing the pressure around the product, sublimation of ice can be achieved. When product quality is an important factor for consumer acceptance, freeze-drying provides an alternative approach for moisture removal.

The heat- and mass-transfer processes during freeze-drying are unique. Depending on the configuration of the drying system (Fig.30.5), heat transfer can occur through a frozen product layer or through a dry product layer. Obviously, heat transfer through the frozen layer will be rapid and not rate-
limiting. Heat transfer through the dry product layer will be at a slow rate due to the low thermal conductivity of the highly porous structure in a vacuum. In both situations, the mass transfer will occur in the dry product layer. The diffusion of water vapor would be expected to be the rate-limiting process because of the low rates of molecular diffusion in a vacuum.

Fig.30.5 Freeze drying System
INTRODUCTION TO HEAT PROCESSING - BLANCHING, PASTEURIZATION, STERILIZATION

THERMAL PROCESSING OF FOODS
BLANCHING

One of the main objectives of the blanching is to destroy enzymic activity in vegetables and some fruits, prior to further processing. Blanching is combined with peeling and/or cleaning of food, to achieve savings in energy consumption, space and equipment costs. To achieve adequate enzyme inactivation, food is heated rapidly to a pre-set temperature, held for a pre-set time and then cooled rapidly to near ambient temperatures. The factors which influence blanching time are:

- type of fruit or vegetable
- size of the pieces of food
- blanching temperature
- method of heating.

The maximum processing temperature in freezing and dehydration is insufficient to inactivate enzymes. In canning, the time taken to reach sterilizing temperatures, particularly in large cans, may be sufficient to allow enzyme activity to take place. It is therefore necessary to blanch foods prior to these preservation operations. Under blanching may cause more damage to food.

The heat resistance of enzymes is characterized by $D$ and $z$ values (Chapter 1). Enzymes which cause a loss of eating and nutritional qualities in vegetables and fruits include lipoxygenase, polyphenoloxidase, polygalacturonase and chlorophyllase. Two heat-resistant enzymes which are found in most vegetables are catalase and peroxidase. Although they do not cause deterioration during storage, they are used as marker enzymes to determine the success of blanching. Peroxidase is the more heat resistant of the two, so the absence of residual peroxidase activity would indicate that other less heat-resistant enzymes are also destroyed. The factors that control the rate of heating at the centre of the product are:

- the temperature of the heating medium
- the convective heat transfer coefficient
- the size and shape of the pieces of food
- the thermal conductivity of the food.
Equipment

The two most widespread commercial methods of blanching involve passing food through an atmosphere of saturated steam or a bath of hot water. Both types of equipment are relatively simple and inexpensive. Steam blanching results in higher nutrient retention provided that cooling is by cold-air or cold-water sprays.

Steam blanchers

At its simplest a steam blancher consists of a mesh conveyor belt that carries food through a steam atmosphere in a tunnel. The residence time of the food is controlled by the speed of the conveyor and the length of the tunnel. Typically a tunnel is 15 m long and 1–1.5 m wide. The efficiency of energy consumption is 19% when water sprays are used at the inlet and outlet to condense escaping steam. Alternatively, food may enter and leave the blancher through rotary valves or hydrostatic seals to reduce steam losses and increase energy efficiency to 27%, or steam may be re-used by passing through Venturi valves. Energy efficiency is improved to 31% using combined hydrostatic and Venturi devices.

Nutrient losses during steam blanching are reduced by exposing the food to warm air (65°C) in a short preliminary drying operation (termed ‘pre-conditioning’). Surface moisture evaporates and the surfaces then absorb condensing steam during Individual Quick Blanching (IQB). Weight losses are reduced to 5% of those found using conventional steam blanching. Pre-conditioning and individual quick blanching are reported to reduce nutrient losses by 81% for green beans, by 75% for Brussels sprouts, by 61% for peas and by 53% for lima beans and there is no reduction in the yield of blanched food.

The equipment for IQB steam blanching (Fig.31.1(a)) consists of a bucket elevator which carries the food to a heating section. The elevator is located in a close fitting tunnel to reduce steam losses. A single layer of food is heated on a conveyor belt and then held on a holding elevator before cooling. The cooling section employs a fog spray to saturate the cold air with moisture. This reduces evaporative losses from the food and reduces the amount of effluent produced. Typically the equipment processes up to 4500 kg/h of food.
Hot-water Blanchers

There are a number of different designs of blancher, each of which holds the food in hot water at 70–100°C for a specified time and then removes it to a dewatering-cooling section.

Fig. 31.1 Blanchers: (a) IQB steam blancher (b) blancher–cooler and (c) counter-current blancher
Developments in hot-water blanchers, based on the IQB principle, reduce energy consumption and minimize the production of effluent. For example, the blancher-cooler has three sections: a pre-heating stage, a blanching stage and a cooling stage (Fig.31.1(b)). The food remains on a single conveyor belt throughout each stage and therefore does not suffer the physical damage associated with the turbulence of conventional hot water blanchers. The food is pre-heated with water that is re-circulated through a heat exchanger. After blanching, a second recirculation system cools the food. The two systems pass water through the same heat exchanger, and this heats the pre-heat water and simultaneously cools the cooling water. Up to 70% of the heat is recovered. A recirculated water-steam mixture is used to blanch the food, and final cooling is by cold air. Effluent production is negligible and water consumption is reduced to approximately 1m³ per 10 t of product. The mass of product blanched is 16.7 – 20 kg per kilogram of steam, compared with 0.25–0.5 kg per kilogram in conventional hot-water blanchers.

In another design, used for blanching broccoli, lima beans, spinach and peas, is the water and food move counter-currently (Fig.31.1(c)).

**Pasteurization**

Pasteurization is a relatively mild heat treatment, in which food is heated to below 100°C. In low acid foods (pH > 4.5, for example milk) it is used to minimize possible health hazards from pathogenic micro-organisms and to extend the shelf life of foods for several days. In acidic foods (pH < 4.5, for example bottled fruit) it is used to extend the shelf life for several months by destruction of spoilage micro-organisms (yeasts or moulds) and/or enzyme inactivation.

The extent of the heat treatment required to stabilize a food is determined by the $D$ value of the most heat-resistant enzyme or micro-organism. As flavors, colors and vitamins are also characterized by $D$ values, pasteurization conditions can be optimized for retention of nutritional and sensory quality by the use of high-temperature short-time (HTST) conditions. For example in milk processing the lower temperature longer time (LTLT) process operating at 63°C for 30 min (the *holder* process) causes greater changes to flavour and a slightly greater loss of vitamins than HTST processing at 71.8°C for 15 s and it is less often used. Higher temperatures and shorter times (for example 88°C for 1 s, 94°C for
0.1 s or 100 °C for 0.01 s for milk) are described as higher-heat shorter-time processing or ‘flash pasteurization’.

**Equipment Used**

**Pasteurization of packaged foods**

Some liquid foods (for example beers and fruit juices) are pasteurised after filling into containers. Hot water is normally used if the food is packaged in glass, to reduce the risk of thermal shock to the container (fracture caused by rapid changes in temperature). Maximum temperature differences between the container and water are 20 °C for heating and 10 °C for cooling. Metal or plastic containers are processed using steam–air mixtures or hot water as there is little risk of thermal shock. In all cases the food is cooled to approximately 40 °C to evaporate surface water and therefore to minimize external corrosion to the container or cap, and to accelerate setting of label adhesives.

Hot-water pasteurizers may be batch or continuous in operation. The simplest batch equipment consists of a **water bath** in which crates of packaged food are heated to a pre-set temperature and held for the required length of time. Cold water is then pumped in to cool the product. A continuous version consists of a long narrow trough fitted with a conveyor belt to carry containers through heating and cooling stages.

A second design consists of a tunnel divided into a number of heating zones. Very fine (atomized) water sprays heat the containers as they pass through each zone on a conveyor, to give incremental rises in temperature until pasteurization is achieved. Water sprays then cool the containers as they continue through the tunnel.

**Pasteurization of unpackaged liquids**

Swept surface heat exchangers or open boiling pans are used for small-scale batch pasteurization of some liquid foods. However, the large scale pasteurization of low viscosity liquids (for example milk, milk products, fruit juices, liquid egg, beers and wines) usually employs **plate heat exchangers**. Some products (for example fruit juices, wines) also require de-aeration to prevent oxidative changes during storage. They are sprayed into a vacuum chamber and dissolved air is removed by a vacuum pump, prior to pasteurization.

The **plate heat exchanger** (Fig.31.2) consists of a series of thin vertical stainless steel plates, held tightly together in a metal frame. The plates form parallel channels, and liquid food and heating medium (hot water or steam) are pumped through alternate channels, usually in a counter-current flow pattern (Fig.31.3). Each plate is fitted with a synthetic rubber gasket to produce a watertight seal and to prevent mixing of the product
and the heating and cooling media. The plates are corrugated to induce turbulence in the liquids and this, together with the high velocity induced by pumping, reduces the thickness of boundary films to give high heat transfer coefficients (3000 –11500 W m\(^{-2}\) K\(^{-1}\)). The capacity of the equipment varies according to the size and number of plates, up to 80 000 l h\(^{-1}\).

Fig.31.2 Plate heat exchanger.

31.3 Counter-current flow through plate heat exchanger:
(a) one pass with four channels per medium;
(b) two passes with two channels per pass and per medium.
In operation (Fig. 31.3), food is pumped from a balance tank to a 'regeneration' section, where it is pre-heated by food that has already been pasteurised. It is then heated to pasteurising temperature in a heating section and held for the time required to achieve pasteurization in a holding tube. If the pasteurizing temperature is not reached, a flow diversion valve automatically returns the food to the balance tank to be repasteurized. The pasteurized product is then cooled in the regeneration section (and simultaneously preheats incoming food) and then further cooled by cold water and, if necessary, chilled water in a cooling section.

**Heat sterilization**

Heat sterilization is the unit operation in which foods are heated at a sufficiently high temperature and for a sufficiently long time to destroy microbial and enzyme activity. As a result, sterilized foods have a shelf life in excess of six months at ambient temperatures.

**In-container sterilization**

The length of time required to sterilize a food is influenced by:

- the heat resistance of micro-organisms or enzymes likely to be present in the food
- the heating conditions
- the pH of the food
- the size of the container
the physical state of the food.

In order to determine the process time for a given food, it is necessary to have information about both the heat resistance of micro-organisms, particularly heat resistant spores, or enzymes that are likely to be present and the rate of heat penetration into the food.

**Retorting (heat processing)**

The shelf life of sterilized foods depends in part on the ability of the container to isolate the food completely from the environment. The four major types of heat-sterilisable container are:

1. metal cans
2. glass jars or bottles
3. flexible pouches
4. rigid trays.

Before filled containers are processed, it is necessary to remove air by an operation termed ‘**exhausting**’. This prevents air expanding with the heat and therefore reduces strain on the container. The removal of oxygen also prevents internal corrosion and oxidative changes in some foods. Steam replaces the air and on cooling forms a partial vacuum in the head space.

Containers are exhausted by:
- hot filling the food into the container
- cold filling the food and then heating the container and contents to 80–95ºC with the lid partially sealed (clinched)
- mechanical removal of the air using a vacuum pump
- steam flow closing, where a blast of steam (at 34 – 41.5 x 10^3 Pa) carries air away from the surface of the food immediately before the container is sealed. This method is best suited to liquid foods where there is little air trapped in the product and the surface is flat and does not interrupt the flow of steam. **Equipment**

Sterilising retorts may be batch or continuous in operation. Batch retorts may be vertical or horizontal; the latter are easier to load and unload and have facilities for agitating containers, but require more floor space. For example, the ‘Orbitort’ consists of a pressure vessel that contains two concentric cages. Cans are loaded horizontally into the annular space between the cages and when full, the retort is sealed. The cages hold the cans against guide rails as they are slowly rotated to cause the headspace bubble to stir the contents.
Continuous retorts (for example, Fig 31.5) permit close control over the processing conditions and hence produce more uniform products. They produce gradual changes in pressure inside cans, and therefore less strain on the can seams compared with batch equipment. The main disadvantages include a high in-process stock which would be lost if a breakdown occurred, and in some, problems with metal corrosion and contamination by thermophilic bacteria if adequate preventative measures are not taken.
KINETICS OF MICROBIAL DEATH, DECIMAL REDUCTION TIME AND THERMAL RESISTANCE CONSTANT, PROCESS LETHALITY

KINETICS OF MICROBIAL DEATH

The destruction of micro-organisms in foods using heat is a well-known phenomenon in the preservation techniques of foods. However the temperature response of vegetative cells and spores is far from uniform. Spores tend to be more heat resistant than vegetative cells which in turn range widely in their heat resistance. Even individual bacteria within a population of a given species show a normal distribution of heat resistance. Thus it is possible to allow heat resistant (or thermoduric) organisms to survive by using a heating regime which is sufficient to destroy bacteria of low to intermediate heat resistance but which fails to kill thermoduric bacteria. These may then thrive within a processing unit, for example, a blancher, and increase the microbial load on a subsequent sterilization operation.

The heat resistance of micro-organisms is also affected by a number of other factors such as:

1. the age of cells; younger cells are less heat resistant,
2. the medium in which growth has occurred; a more nutritious medium increases heat resistance,
3. moisture content; dry foods tend to require more severe heat treatment during sterilization,
4. the presence of sodium chloride, proteins and fats all increase heat resistance,
5. pH.

Decimal Reduction Time and Thermal Resistance Constant

The decline in the number of micro-organisms when subjected to heat is asymptotic with time and therefore it is not possible to eliminate all microorganisms. There is a logarithmic relationship between the number of survivors of a given microorganism ‘n’ and time ‘t’ at any given temperature (Figure 32.1). This is known
as a **survivor curve**. The gradient of the survivor curve increases markedly with temperature.

![Survivor curve](image)

**Fig.32.1 Survivor curve**

The decimal reduction time $D$ is defined as the time for a tenfold reduction in the number of survivors of a given micro-organism, in other words the time for one log cycle reduction in the microbial population. Higher values of $D$ imply, at a given temperature, greater resistance of micro-organisms to thermal death. Because $D$ depends upon temperature, the temperature in °C is appended as a subscript. Thus $D_{121.1}$ is the time required at 121.1 °C to reduce a microbial population by 90%. A temperature of 121.1 °C (or 250°F) is used as a common reference point and therefore, because of its importance, this is sometimes referred to as $D_0$.

The logarithmic decline in the number of organisms $n$ is represented by

$$\frac{dn}{k_n \, dt}$$

where $k$ is a rate constant. Therefore the equation of the line in survivor curve is represented by

$$t \, D (\log n_1 \, \log n_2) \text{ or}$$

$$t \, D \log \frac{n}{n_2}$$

where $n_1$ and $n_2$ are the initial and final number of micro-organisms, respectively. The value of $D$ is independent of the initial population of microorganisms. **Example**
A sample of fixed volume was held at a constant temperature and the number of microorganisms in the sample measured as a function of time. Calculate the decimal reduction time.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Number of micro-organisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>$2.00 \times 10^5$</td>
</tr>
<tr>
<td>2.0</td>
<td>$4.31 \times 10^4$</td>
</tr>
<tr>
<td>4.5</td>
<td>$6.32 \times 10^3$</td>
</tr>
<tr>
<td>6.0</td>
<td>$2.00 \times 10^3$</td>
</tr>
<tr>
<td>7.5</td>
<td>$6.32 \times 10^2$</td>
</tr>
</tbody>
</table>

**Sol:** A plot of the natural logarithm of the number of organisms against time gives a straight line of gradient 3 min. Hence $D = 3$ min.

The concept of decimal reduction time allows the probability of the survival of spores to be predicted. For example, if a process is sufficiently effective to produce 10 decimal reductions in the microbial population then, if a canned food which is to be sterilised contained initially $10^{10}$ spores per can, the final population would be one spore per can. Alternatively, for an initial population of $10^5$ spores per can, the final population would be $10^{-5}$ spores per can. This latter figure is interpreted to mean that one can in $10^5$ is likely to contain a spore. Such a process is referred to as a **10D process**.

![Figure 32.2 Thermal resistance curve.](image)

A plot of the logarithm of decimal reduction time against temperature is generally linear. This is known as a thermal resistance curve (Figure 32.2) from which a thermal resistance constant, or more commonly a $z$ value, can be defined.
The z value is the temperature change for a ten-fold change in decimal reduction time D and larger z values indicate greater heat resistance to higher temperatures. Thus, for an organism for which \( z = 13 \) K, an increase in temperature of 13 K will produce a decrease in the decimal reduction time of 90%. For *clostridium botulinum* the value of z is 10K. The characterization of the kinetics of microbial death in terms of decimal reduction time and thermal resistance constant is the first step in specifying a sterilization process.

**Process Lethality**

Having established a method of describing microbial death rates it is necessary to find a way of characterizing a sterilization process so that its effectiveness for any given application can be judged. Because a range of temperature/time combinations can be used to achieve the same reduction in population of a given micro-organism, different sterilization processes can be compared using a quantity known as total process lethality, \( F \), which represents the total temperature/time combination to which a food is subjected. Less commonly this is called **thermal death time**.

\( F \) is the time required (usually expressed in minutes) to achieve a given reduction in a population at specified temperature. For example, a process lethality of \( F = 2.5 \) implies heating for two and a half minutes at the reference temperature and for a specified z value. The reference temperature is usually appended as a subscript and the z value as a superscript giving, for example, \( F_{121.1}^{10} \). These particular conditions are used as a reference value of \( F \) which is designated as \( F_0 \).