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Preface

The increasing global demand for processed foods has led to a greater prominence of the food industry, its specific needs and processing challenges. Consequently, in recent times the role of the engineer in the food industry has gained considerable prominence. In contrast to other more traditional processing industries, the raw materials or ingredients that are used tend to be of greater complexity in nature. While processing conditions are also more moderate in that temperatures even in hottest ovens may not exceed 200°C and pressures rarely exceed one or two bar, the materials themselves are highly complex in composition, textural and flavour characteristics. During their handing and processing, many changes to their properties occur. The extent of these changes is often a strong function of their process history. In the food industry one plant frequently is required to perform one purpose. To produce a product which is constituent and desirable to the consumer's expectations in terms of appearance, texture and taste all year round from raw materials which may be derived from different sources or suppliers together with seasonal variability, requires a sound understanding of the physical and chemical properties of the food materials being processed and the detailed understanding of the function of various units operations. In all of this, food safety is paramount. Understanding the nature and sources of contamination is essential, and its control critical to ensure that the processed foods are safe to eat. Product safety is as critical as process safety.

This e-book is aimed at undergraduates and practitioners who have an interest in food process engineering. It is designed to provide an overview of the many operations associated with the processing of raw food materials to produce products which are creative, palatable and safe to eat. If you should find any errors or inaccuracies, or wish to offer feedback or suggestions for improvements, you are encouraged to email me. I hope the reader will find this e-book useful.

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1 Introduction

Over the past couple of decades, the role of the engineer in the food industry has gained considerable prominence. The food processing industry is extremely complex, diverse and evolved. With a consumer market becoming evermore sophisticated and demanding, there is a continual need for process innovation. Even allowing for the demands of the consumer for product consistency and quality, the consumer expects excitement, novelty, value for money and a product that is safe in tamper-proof packaging. For the food process engineer, the challenge is to use process plant and associated equipment which is sufficiently flexible to respond to any changes in demand.

The complexity and challenges of food processing engineering is best illustrated by considering the mixing criteria used in the food industry. Process engineers will be more familiar with the handling and mixing of robust components with the aim of achieving homogeneity in which liquids have low viscosity or exhibit straightforward Newtonian behaviour and where scale-up is based on simple power-to-volume ratios.

In contrast, the criteria for food mixing involve ingredients which have complex components with each exhibiting very different chemical and physical properties. They often have high viscosities and exhibit non-Newtonian behaviour. They may also be fragile in nature and easily damaged during high shear mixing in which there is a complex and intimate relationship between the mixing patterns and product characteristics. The scale-up of equipment is governed by the need to maintain textural properties of food.

All of this is further complicated by the need to maintain product quality in terms of texture, colour, appearance, rheology, functionality, aeration, droplet size and particulate integrity particularly when the raw materials used are subject to possible day-to-day and seasonal variations. It is essential that the food products are safe to eat, free from contamination, produced in a safe environment that conforms to food safety standards and other legal requirements. Finally, the process engineer must ensure that the process operation is energy efficient and has minimal environmental impact.

Further, the food process engineer is not only required to have a high regard for all the technical aspects associated with the processing of foods but that the needs and requirements of the consumer are fully appreciated. Consumers are increasingly demanding foods which are nutritious and healthy such as fortified organic and minimally processed foods. There is also a considerable demand for foods which are highly processed such as sausages, burgers, baked beans and dehydrated foods, and foods which have long shelf-life and total sterility such as canned and bottled foods with packaging that is tamper-proof yet can be easily opened.

Yet if that isn't sufficient, the food process engineer must also have a high regard for the food and drink marketplace which is characterised by short time-to-market and competitiveness, production innovation and product complexity. Production runs are becoming ever shorter as tastes and fads change.

While food processing may be classified into either chemical, physical or biological operations, there are many major issues affecting food process engineering including molecular genetics with the use of GMOs, the use of animal cloning, new regulatory procedures, ethical issues, public concerns, planetary considerations and a number of major socio-economic considerations. The underlying requirements for technological progress in food processing are a minimum of risks acceptable for the benefits gains, as well as a full public understanding. The role of the food process engineer is critical in all of this.

1.1 Food Processing

The fundamental necessity for food is to sustain life. The principal reason for the processing food is to make it microbiologically safe to eat. Processing foods can transform unpalatable or unacceptable raw materials into attractive and desirable products.

Nutritional requirements are required to be met throughout the year. Before the development of preservation techniques, winter diets were based mainly on cereals, grains and fruit that were dried on the plant before harvesting. In Northern Europe livestock such as pigs and cows were once slaughtered in the autumn, as there were insufficient foods available to sustain them during the winter months. The meat was then preserved by salting and curing allowing it to be available for out-of-season consumption.

In the processing of foods, it might be assumed that a food product ought to resemble the appearance and taste of the raw food material. While this is the case for tinned or frozen garden peas, foods such as smoked sausages and canned baked beans are quite different from their fresh precursors and are, in some cases, even more popular.

Over the centuries, producers and consumers have become geographically separated through increased urbanisation; supermarkets have flourished which can now handle foods with a minimum of specialised equipment. Tinned and bottled products have a long storage life and require little specialist storage. Diary products with a short shelf-life such as pasteurised milk require little more than refrigeration.

1.2 Food Safety and Control

The highest priority of the food industry is to ensure that the foods which are processed are safe to consume. In recent times, there has been much publicity concerning major issues such as BSE in beef, genetically modified crops, nitrates in water, dioxins in livestock, listeria in blue cheese, E. coli 0157 in cooked meats and melamine in infants' milk to name but a few. A major cause of illness in humans is due to foods contaminated due to poor processing conditions, sanitation, working practices and packaging.

Storing food to prevent spoilage often involves destroying or inactivating contaminating pests such as insects, rodents and microorganisms. When these are capable of producing disease in humans (that is, they are pathogenic) this becomes even more important. The cooking of meat, for example, destroys both spoilage and pathogenic organisms. If care is taken by the provision of a suitable barrier, as in canning, to ensure that they are not reintroduced, the storage life of the product may be extended from a few to hundreds of days.

Once a contaminated food is ingested, the organism continues to multiply inside the body, reaching a population size sufficient to cause noticeable symptoms. Depending on the organism and food, control is either by ensuring that the contaminating organism is unable to infect the food in the first place or by destroying it during a cooking process.

As examples, the harmful bacterium *Staphylococcus aureus*, is readily destroyed by the normal cooking process. Its toxin, however, is very resistant to boiling. Botulism is a very serious type of poisoning caused by eating food containing the toxin produced by the bacterium *Clostridium botulinum* for which the spores are very resistant to many cooking processes.

It is not always necessary to eliminate all contaminating organisms. It may often be necessary to ensure a satisfactory level of safety under given storage conditions. Commercial sterilisation is designed to destroy all micro-organisms and spores, which if present, could multiply in the food while pasteurisation is designed to destroy only those microorganisms which are pathogenic. It makes no attempt at destroying all the microorganisms that may be present.

The growth and viability of micro-organisms in foods is influenced by the availability of water. The presence of high concentrations of osmotically active substances such as salt or sugar also influences growth and viability as well as the presence of acids. Preserved foods vary from neutral pH to acidic. Only fungi are likely to grow below pH 3.7 although a mild heat treatment is often desirable for foods in this category to stop fungal spoilage and inactivate enzymes. Acidic foods, such as fruit, require pasteurisation to destroy vegetative organisms. It is not always necessary for spores to be destroyed in this pH range, as any spores present are unable to germinate below pH 4.5. Low acidic foods such meat, fish and milk require sterilisation to ensure that resistant spores are destroyed.

Since heat treatment often affects the quality, appearance, texture and taste of food as well as micro-organism content, the choice of heat treatment conditions is important. Heat is an effective way of eliminating microbial hazards when combined with adequate hygienic practices, such as the hygiene of personnel and sterilisation of equipment. This also helps to minimise the chance of infection with the larger human parasites such as tapeworms and roundworms.

Heat treatment is a requirement by law for many products. UK and European regulations require that food consisting of meat, fish, milk and egg must be stored below 10°C or above 62°C unless displayed for sale or intended for immediate consumption. This is because the pathogenic bacteria, *Salmonellae, Staphylococci, Streptococci* and *Clostridia* are unable to reproduce outside this temperature range.

1.3 Food Quality

The properties and qualities of foods, which affect acceptability to the consumer, are referred to as organoleptic properties. It is impossible to quantify the definition of food quality because it varies between each person's expectations. Food may be liked or indeed disliked as a consequence of many factors which may be religious, cultural, social, psychological or on health grounds, as well as certain expectations of appearance, texture, flavour and aroma.

Consumers are generally concerned that the quality of a food product has a consistent standard, which may be defined in terms of its organoleptic properties. Food producers, farmers, caterers and food manufacturers must therefore be capable of maintaining certain objective quality standards. The quality of certain products can be tested by a trained panel of experts who can detect whether a product has attained a necessary standard. However, it is rather expensive to use expert panels. Mechanical or electronic techniques and instruments are therefore frequently used which are capable of providing an objective measurement of a particular attribute.

1.3.1 Temperature

The temperature of a food is the easiest attribute to measure and involves a thermocouple linked to a data logger. This can provide important information on the physical, chemical and microbiological changes taking place before, during and after processing.

1.3.2 Colour

The perception of colour depends on both physical and psychological factors. Spectral colour is defined by the predominant wavelength of light while saturation is defined as the degree of mixture of that dominant colour with white. Brightness, on the other hand, is associated with the total amount of light energy reflected or transmitted by the food. The colour of food is most easily measured by matching with standard colours under standard lighting conditions.

Standard lighting colour, along with humidity and temperature control is used during sensory analysis with trained assessors as shown in the photograph below.

1.3.3 Texture

Texture is a complex property relating to the physical and chemical structure of the food. Foods range from hard to soft, brittle to chewy. Hardness is a measure of the force required to cause a given deformation. Softness means that food can be squashed easily between the teeth although disintegration may occur. Cohesiveness and gumminess is the strength which holds the food together and the resistance to the withdrawal of teeth, respectively. In contrast, chewiness is the energy needed to disintegrate the food. The elasticity of foods is the rate at which a deformed material returns to its original shape and adhesiveness is the work necessary to overcome the attractive forces between the surface of the material and the other surfaces in contact with it. Brittleness is the force necessary to cause fracture. Applied to liquids, viscosity is a measure of its thickness or thinness.

To measure the texture of foods, various instruments such as penetrometers are used. These are probes which travel a certain distance into a sample of food when subjected to an applied force. Viscometers are used to measure the consistency of sauces, dressings, purées and batters.

1.3.4 Flavour and Taste

Foods may be liked or disliked based on flavour and taste alone. Flavour components may be present in food in minute quantities. Flavour can be distinguished into the four elements of sweetness, acidity, bitterness and salt. All are sensed by specific cells on the tongue. Taste is these basic flavours combined with odours, sensed in the nose, which arise from the volatile components of the food. Sweetness, for example, is associated with sugars while acidity is associated with organic acids such as vinegar, or mineral acids such as phosphoric acid in cola. A number of compounds in addition to common salt give rise to saltiness, including sulphates, bicarbonates, nitrates and phosphates of calcium, potassium, magnesium and ammonium. Bitterness arises from tannins in tea.

2 Constituents of Food

2.1 Introduction

In order to process foods by converting raw materials into creative, desirable, attractive and appealing products that are both safe to consume and have year-round consistency, its essential that the food process engineer has a firm understanding of the food constituents and their interacting behaviour. Foods by their very nature are often complex and multi-component in composition. As well as water, foods also include carbohydrates, proteins, fats and oils. Also present in lesser but nonetheless important amounts are flavours, vitamins, minerals and additives such as preservatives. Not all foods contain all of these components nor in equal quantities.

2.2 Water

In many foods, water is the most abundant constituent. Fruit, vegetables, juices, milk, fish and meat all contain high levels of water. Cheese, bread, biscuits and cakes on the other hand, contain relatively less levels of moisture while dehydrated foods and powders contain virtually none. The presence of moisture is critical in the textural properties of a food but is often responsible for its microbial, enzymatic and chemical deterioration.

2.3 Carbohydrates

Carbohydrates provide much of the energy in our diets. Most is found in the form of polysaccharides as starch derived from plant cells. Simple sugars as mono or disaccharides are mainly derived from cane, beet sugar and honey which contribute to sweetness, texture and colour in foods.

The main constituents of starch are amylose and amylopectin. Starch in maize is entirely made up of amylopectin molecules, whereas in wheat a quarter is amylose with the remainder being amylopectin. Starch does not dissolve in cold water, but when heated to 60^{o}C, water diffuses through the walls of the starch granules, causing swelling and the viscosity of the starch suspension to increase. Further heating causes the granules burst giving a viscous gel. Thick sauces and gravies are prepared using flour. When starch is heated in an acidic medium, however, the starch becomes partly hydrolysed to a mixture of sugars and dextrins causing a reduction in viscosity.

There are many types and derivations of sugar types. Many are used in the manufacture of confectionary. Non-crystalline confectionary includes caramels, brittles, marshmallows and gumdrops whereas crystalline confectionary includes fudge and fondants.

Candies are made of sucrose, water or some other liquids. Their manufacture involves producing a supersaturated sucrose solution. This involves heating the concentrated sugar solution and allowing it to cool undisturbed. Upon cooling the sugar crystallises. For crystallisation to occur, nuclei must form either spontaneously or by seeding to initiate crystallisation. The size of the resulting crystals depends on the number of nuclei, rate and temperature of crystallisation, agitation and impurities in the solution. Butter is often added to deliberately interfere with the formation of crystal growth.

Caramelisation is the application of heat to the point that sugars dehydrate and breakdown and polymerize. This is called "*non-enzymatic browning*" because it does not involve enzymes. Caramel has a pungent taste and is often bitter. It is much less sweet than the original sugar from which it is produced, is non-crystalline, and is soluble in water. Both the extent and rate of the caramelisation reaction are influenced by the type of sugar being heated. Galactose, sucrose and glucose all caramelise around 160°C whereas fructose caramelises at 110°C and maltose at about 180°C.

The Maillard reaction is the reaction between the amino group of a protein or amino acid and the reducing group of a reducing sugar. The type of sugar and the type of amino acids influence the colour obtained which may range from yellow to red. Not all sugars are reducing sugars. The most effective reducing sugars are fructose, glucose, maltose, galactose and lactose. Note that the commonly used sugar sucrose is not a reducing sugar.

2.4 Fats and oils

As well as being a major source of energy in the diet, fats and oils play an important role in the palatability of foods. In terms of bakery properties both fats and margarine are important in that they:

- influence eating properties
- influence flavour release
- influence batter and baking properties
- provide coherence and consistency to doughs
- allow aeration to be possible
- contribute to colour
- provide a shining or glossy appearance to bread
- influence shelf-life through moisture loss reduction

The main difference between fats and oils is that oils are liquids at room temperature whereas fats are solid. The term "fat" is commonly used for lard (pork fat) or tallow (beef fat). The extraction of fats and oils is achieved by:

- Rendering: used mostly for fat tissue from slaughtered animals. This includes beef, pork, deer, sheep and fish.
- Pressing: used for oil-containing seeds and fruits. The colour, taste and aroma are specific to the type of seed or fruit. Oils include peanuts, olive, corn, sesame, soy, sunflower, rape and palm.
- Extraction: used for fat-containing material using organic solvents.

Most refined fats and oils are used as a raw material for the production of margarine, mayonnaise and fat for frying, baking and roasting. The process of changing their consistency includes:

- Hydrogenation: This hardening process gives a firmer consistency to oils.
- Fractionation: Used to separate fats into fractions with different melting points.
- Esterification: Used to give a suitable firmness and spreadability as fats.

Edible fat is a mixture of animal and/or vegetable fats. The term "butter" is applied only for the fatty substance from milk, which has been obtained from the butter-making process. The term "margarine", on the other hand, is a copy of butter.

The type of fat or oil present directly affects the textural qualities of foods, including a smooth mouth-feel and the flavour of many dishes and foods. Chips cooked in a vegetable oil have a different flavour from those cooked in lard. The texture of a fat is dependent on its physical state; suet (beef fat) is hard at room temperature of 20°C, whereas vegetable cooking oils are liquid and some margarines are soft at this temperature. The melting point of a fat or oil depends on the fatty acid chain length and their degree of saturation.

Chemically, fats and oils consist of glycerol esterified with three fatty acids to form a triglyceride. There are more than 50 different fatty acids and vary structurally in terms of chain length (2 to 24 carbon atoms) and the number of double bonds between the carbon atoms. Where there are more than one or more double bonds, they are termed mono or polyunsaturated fatty acids, respectively (see Tables 2.1 and 2.2).

The melting point of a fat increases with fatty acid chain length (Table 2.3). Suet, which is composed of stearic acid, has a higher melting point than butter, which contains butyric acid. The presence of double bonds lowers the melting point. Olive oil contains unsaturated oleic acid and melts at a lower temperature than stearic acid. Oleic acid can be converted by the addition of hydrogen into saturated stearic acid giving a harder fat.

A high percentage of unsaturated fatty acids in triglycerides results in a more liquid consistency at room temperature while a high percentage of saturated fatty acids gives a more solid consistency (Table 2.4). In vegetable oils, the double bond present in the saturated fatty acids are called cis double bonds and can be transformed into the trans isomer as in the preparation of margarine. Trans fatty acids are said to increase the serum cholesterol and thus contribute to the causes of heart disease. The consumption of unsaturated fatty acids with cis double bonds, and in particular cis-cis linoleic acid, is therefore recommended in preference to animal fats in which trans fatty acids occur.

In addition to triglycerides, natural fats and oils contain other components. These include waxes, phospholipids and hydrolysis products (di- and mono-glycerides and fatty acids) as well as other non-related chemicals such as sterols, pigments such as carotenes and chlorophyll, and vitamins such as A, D, E and K.

With the exception of frying, there is a structural change to fats and oils during processing. With intense heating, fats are oils increase in viscosity with a darkening colour and the formation of polymeric compounds. With repeated heating, olive oil and other oils may undergo a reaction that leads to oxidative rancidity, associated with bitter "off" flavours and acrid odours, found in vegetable oils. Oxidative rancidity is affected by the presence of metals such as copper or iron, blue or ultra-violet light, moisture, salt and haematein compounds found in meat.

When fat is heated to a very high temperature as in frying, it begins to smoke. This smoke consists of gaseous products resulting from the breakdown of fats into glycerol and free fatty acids. Glycerol itself may break down to give a sharp smelling, irritant compound called propenal (or acrolein) which gives an unpleasant flavour to the cooked food. It is therefore desirable to use fats or oils with a high smoke point for frying. Even so, prolonged and repeated use results in rancidity and an increase in fat viscosity, as rancid products may combine with fats to increase the chain length of the fatty acids.

The term margarine applied to certain types of shortenings as well as spreads and is manufactured from vegetable oils that have been hydrogenated or crystallised to form the required spreading texture. The vegetable oils may also be blended with lesser quantities of animal fats. Like butter, there is a legal requirement for margarine to contain no less than 80% fat. Since oils are virtually all fat, water is added usually in the form of milk or cream to produce the desired water-in-oil emulsion. Emulsifiers are also added along with salt, butter flavour and a permissible level of preservatives such as sodium benzoate. Vitamins A and D may also be added.

In the manufacture of margarine, separate preparations are made of water and fat-soluble ingredients. The two mixtures are then emulsified with vigorous agitation to form a continuous phase and then chilled before passing into a crystalliser to solidify further and plasticise the fat. The semi-solid margarine is finally continuously extruded and packaged.

Table 2.1 Saturated Fatty Acids

Molecular Formula	Common name	Systematic name
$C_2H_4O_2$	acetic	…
$C_3H_6O_2$	propionic	…
$C_4H_8O_2$	n-butyric	…
$C_6H_{12}O_2$	caproic	n-hexanoic
$C_8H_{16}O_2$	caprylic	n-octanoic
$C_9H_{18}O_2$	pelargonic	n-nonanoic
$C_{10}H_{20}O_2$	capric	n-decanoic
$C_{12}H_{24}O_2$	lauric	n-dodecanoic
$C_{14}H_{28}O_2$	mystric	n-tetradecanoic
$C_{16}H_{32}O_2$	palmitic	n-hexadecanoic
$C_{18}H_{36}O_2$	strearic	n-octadecanoic
$C_{20}H_{40}O_2$	arachidic	n-eicosanoic
$C_{22}H_{44}O_2$	behanic	n-docosanoic
$C_{24}H_{48}O_2$	lignoceric	n-tetracosanoic
$C_{26}H_{52}O_2$	cerotic	n-hexacosanoic

Table 2.2 Unsaturated Fatty Acids

Molecular Formula	*Common name*	*Systematic name*
$C_{16}H_{30}O_2$	palmitoleic	9-hexadecenoic
$C_{18}H_{30}O_2$	linolenic	9,12,15-octadecatrienoic
$C_{18}H_{30}O_2$	γ- linolenic	6,9,12-octadecatrienoic
$C_{18}H_{30}O_2$	eleostearic	9,11,13-octadecatrienoic
$C_{18}H_{32}O_2$	linoleic	cis-cis-9,12-octadecadienoic
$C_{18}H_{34}O_2$	oleic	cis-9-octadecenoic
$C_{18}H_{34}O_2$	elaidic	trans-9-octadecenoic
$C_{18}H_{34}O_2$	vaccenic	11-octadecenoic
$C_{20}H_{32}O_2$	arachidonic	5,8,11,14-eicosatetaenoic
$C_{22}H_{34}O_2$	clupanodonic	4,8,12,15,19-docosapentaenoic

To determine the structural formula, the double bond is counted back from the carboxyl group in which the first carbon atom is counted as number 1.

Table 2.3 Melting Points and Occurrence of Some Fatty Acids

Formula	*name*	*Melting pt °C*	*Source*
$C_4H_8O_2$	n-butyric	-6	Butter
$C_6H_{12}O_2$	caproic		Butter
$C_8H_{16}O_2$	caprylic	16	Butter, coconut oil and palm nut
$C_{10}H_{20}O_2$	capric	31	Butter, coconut oil and palm nut
$C_{12}H_{24}O_2$	lauric	44	Coconut oil and palm nut
$C_{14}H_{28}O_2$	mystric	54	Coconut oil, nutmeg and lard
$C_{16}H_{30}O_2$	palmitoleic	33	Peanut oil
$C_{16}H_{32}O_2$	palmitic	63	Animal fats
$C_{18}H_{30}O_2$	linolenic		Linseed
$C_{18}H_{34}O_2$	oleic		Animal fats
$C_{18}H_{36}O_2$	strearic	69	Animal fats
$C_{20}H_{40}O_2$	arachidic		Peanut oil
$C_{24}H_{48}O_2$	lignoceric		Peanut oil
$C_{22}H_{34}O_2$	clupanodonic		Whale, cod liver and fish oil

Table 2.4 Melting Points of Some Triglycerides

S-S-S	72 °C
P-P-P	65 °C
S-P-P	62 °C
E-E-E	42 °C
S-P-O	39 °C
P-O-P	37 °C
P-S-O	36 °C
S-O-P	35 °C
O-P-P	34 °C
O-O-S	23 °C
O-O-P	19 °C
O-O-O	5 °C
L-L-L	-10 °C

NB: S=Stearic, P=Palmitic, O=Oleic, E=Elaidic, L=Linoleic

2.5 Proteins

As well as providing nutritionally essential amino acids, proteins contribute to the acceptability of foods. Many of the properties if proteins are also utilised in many cooking processes. When meringue is made, for example, the egg white protein complex albumen is beaten allowing air to be incorporated. As the albumen foam is gently heated in an oven, the transparent liquid protein denatures, turns white and solidifies, thus ensuring that the structure of the meringue is held firm.

Meat is a major dietary source of protein, which consists of muscle cells held in a matrix of connective tissue, composed of the protein collagen. This is usually dispersed throughout the muscle, but forms major concentrations as gristle near skeletal joints. When meat is cooked the collagen of the connective tissue is hydrolysed to gelatine. Gelatin, in common with other proteins, has the ability to imbibe water and swell. It dissolves in warm water to form a colloidal solution, but gels when cooled, as occurs when jellies are made, or when the juice from roast meat is allowed to cool and set. Muscle proteins also have the ability to hold water in a bound form; this is termed the water binding capacity of the protein. When meat is cooked this capacity is reduced, so that the muscle proteins lose water and shrink. As this occurs, so the muscle fibres themselves become tougher, although the connective matrix softens as a result of gelatinisation.

Plant and animal proteins are composed of amino acids, which can be combined in a variety of ways to form muscle, tendons, skin, fingernails, feathers, silk, haemoglobin, enzymes, antibodies and hormones. Proteins are therefore polyamides and the order in which amino acids are sequentially joined together in a protein molecule is called the primary structure. Unsurprisingly, the word protein is derived from the Greek *proteios,* which literally means *primary*.

The shape into which a protein molecule folds its backbone is called the secondary structure. Further folding of the backbone upon itself by molecular forces to form a spherical structure is called the tertiary structure. The secondary and tertiary structures are collectively referred to as the higher structure of the protein. The functional properties of a protein are due specifically to the higher structure.

The precise shape or conformation of a protein molecule is due to weak non-covalent intermolecular forces across the higher structure. These include hydrogen bonding between side chains, disulphide cross-links, and salt bridges (ionic bonds such as $RCO_2^- {}^+H_3NR$ between side chains). The most stable higher structure is the one that has greatest number of stabilising interactions.

The orderly and distinguishable secondary structure consists of α helical structures and β (or pleated) sheets. Helical structures involve hydrogen bonds between one amide-carbonyl group and an NH group while the sheet arrangement consists of single protein molecules are lined up side by side and held together by hydrogen bonds between the chains.

Milk and egg white are soluble globular proteins. Their solubility is due to their tertiary structure. Polar hydrophilic side chains are positioned on the outside of their spherical structure increasing water solubility while non-polar hydrophobic side chains are arranged on the inside surface where they may be used to catalyse non-aqueous reactions. The unique surface of globular proteins enables them to recognise certain complementary organic molecules. This recognition allows enzymes to catalyse certain reactions but not others.

Protein denaturation is the loss of the higher structural features caused by disruption of hydrogen bonding and the non-covalent forces that hold it together. The result is the loss or change in many of the functional properties of the protein. Pressure, temperature, pH, detergents, radiation, oxidising or reducing agents can also cause denaturation. Boiling an egg is an example of an irreversible denaturation in which the colourless albumins unfold and precipitate resulting in a white solid. Likewise, when milk sours, the change in pH arising from lactic acid formation causes curdling or precipitation of soluble proteins.

Some proteins are quite resistant to denaturation, while others are more susceptible. Denaturation may be reversible if a protein has been subjected to only mild denaturing conditions. Under certain conditions a protein may resume its natural higher structure in a process called renaturation. Renaturation, however, may be very slow or may not actually occur at all.

2.6 Vitamins and Minerals

Vitamins and minerals are substances normally present in many different foodstuffs in very small amounts and are essential in the diet to maintain normal growth and development of the human body. The vitamin and mineral requirement of the human body is usually adequately met by a balanced diet. A lack of vitamins and minerals cause a number of different unpleasant deficiency symptoms to occur which disappear again as soon as the vitamin or mineral is supplied in sufficient quantity. Deficiency symptoms can also be caused by stress and disease. People nowadays are increasingly taking vitamin and mineral supplements in pill form with the notion that by taking them it will prevent these symptoms from occurring and strengthen their immune systems as well as cure cancer and prevent rheumatism. Little, however, is known about exactly how vitamin pills affect the body. New functions of vitamins in the body are still being discovered.

Minerals are the constituents left in biological materials after incineration. They are classified into being either abundant or trace quantities as shown in Table 2.5.

Table 2.5 Abundant and Trace Minerals in the Human Body

Abundant Mineral	$g.kg^{-1}$	Trace Mineral	$mg.kg^{-1}$
Calcium	10-20	Iron	70-100
Phosphorus	6-12	Zinc	20-30
Potassium	2-2.5	Copper	1.5-2.5
Sodium	1-1.5	Manganese	0.15-0.3
Chlorine	1-1.2	Iodine	0.1-0.2
Magnesium	0.4-4	Molybdenum	0.1

Within the body, vitamins behave as biological catalysts starting chemical reactions without themselves becoming involved. Some vitamins, however, are only a part of a catalyst. Vitamin K, for example, is important for the blood's ability to clot, or coagulate. New-born babies, whose intestinal bacteria are not yet fully developed, are sometimes given an injection of vitamin K shortly after birth to enable their blood to coagulate normally.

Perhaps surprisingly, most vitamins were only first discovered a hundred years ago. It was the Polish biochemist Casimir Funk in 1911 who claimed that food generally contained vital substances which provided the necessary protection against the diseases beriberi, pellagra, rickets and scurvy. These he called *vitamins:* a word he derived from *vita* meaning *life* and *amine* based on the fact that they contain nitrogen.

Since the isolation of vitamin A, from butter and eggs in 1913, all 13 vitamins have been extracted from foods and can now be synthesised in the laboratory. Of these, four are fat soluble (A, D, E and K) with the rest being water soluble (C and the B vitamins). All with the exception of B12 can be synthesised with a total annual world production of vitamins in the order of 123,000 tonnes in an industry worth in excess of $ 5.0 billion with Hoffman-La Roche and BASF being the world's major producers.

A recommended daily allowance (RDA) serves as a useful guide for evaluating the adequacy of a person's nutritional intake. The RDA values vary from one country to another but do allow consumers to estimate whether their daily intake meets recommended levels. The amount of a vitamin in a food product is expressed on the food label as a percent of the RDA.

Even though severe vitamin deficiency can lead to classical deficiency diseases such as scurvy, deficiency symptoms do not always present themselves immediately. Marginal vitamin C deficiency may weaken the body's immune system long before the signs of scurvy appear. Symptoms of marginal vitamin B deficiency may include a loss of appetite and irritability.

It is sometimes wrongly assumed that exceeding the RDA solves the problems of deficiency. Generally, the intake of vitamins is safe beyond the RDA. Fat-soluble vitamins require fat to be absorbed in the intestine and is the reason why they should be taken at meal times. Excessive amounts of fat-soluble vitamins are stored in the body's fatty tissues so it is important not to overdose on this form of vitamin. Harmful side effects or poisoning can result by taking too high a dosage over a long period. Ten times the RDA for vitamin A, for example, is considered safe but above that it can cause damage to the liver, spleen, cause weakness and fatigue as well as cause poor vision and weight loss.

Water-soluble vitamins do not present the same risk since any excess is excreted in the urine. On the other hand, vitamin deficiencies occur more easily within this group.

2.6.1 Fat Soluble Vitamins

Vitamin A: Found in liver and milk, vitamin A is necessary for maintaining the mucous membranes of the respiratory and digestive systems, and the cells of the skin in a healthy condition. Vitamin A is also involved in the visual cycle chromo proteins in the blue, green and red cone cells and the rods in the retina. The chromo proteins are formed in the dark. In the light they break down releasing energy, which cause impulses in the sight nerves. A lack of vitamin A impairs vision making it harder to see in the dark. The magical effects of liver have been known for millennia. The ancient Egyptians ate liver to be able to see better in poor light while the Greek physician Hippocrates (460-377 BC) was reputed to have cured night blindness with ox liver. Fritz Lipmann (Germany) was awarded the Nobel Prize for Medicine in 1953 for the discovery of the coenzyme A.

Retinol acid, a form of vitamin A, is effective in the treatment of acne since it opens the pores of the skin. Cream preparations, which contain retinol acid, however, also increase the skin's sensitivity to ultraviolet light causing the skin to become easily irritated on exposure to the sun.

Beta-carotene is a preliminary stage of vitamin A or pro-vitamin and occurs as the orange colouring in certain vegetables, and in particular, carrots. It was originally thought that the vitamin might be effective against lung cancer.

Vitamin D: The main function of vitamin D is to help the body to absorb phosphorus and deposit calcium in the bones so that they become hard and strong. A lack of the vitamin may therefore be the reason for a higher occurrence of broken hips in the elderly. Children and young people require additional calcium to build up their bones, otherwise there is a risk that they could develop rickets. The symptoms of rickets are a hollow chest, curved back, bow legs and loose teeth. Vitamin D is considered the most poisonous of all vitamins. Excessive doses can cause nausea, thirst, loss of weight and a risk of kidney failure.

Vitamin D is found in oily fish, cod-liver oil and fish oil, and is also created in the skin when it is exposed to the sun. People who live in countries with little sunshine do not always produce sufficient amounts of vitamin D to cover their needs.

Vitamin E: An important antioxidant in that it neutralises free radicals within the body. Solar radiation, air pollution and the degradation of proteins are the cause of free radicals and reactive oxygen compounds are constantly being formed within the body. Unless controlled, free radicals can destroy cell membrane as well as alter genetic material (DNA) increasing the risk of cancer. Like other antioxidants vitamin E can prevent this damage from occurring.

Vitamin E is responsible for regulating the balance of certain hormones in the body. The male sex hormone testosterone depends on vitamin E to produce sperm in the testicles while the female hormones oestrogen and progesterone need both vitamin E and B to be biologically active. Vitamin E is therefore important for normal pregnancy and may lead to sterility in men if deficient. Found widely in wheat, cereal, peas and lettuce it is an approved food additive.

Vitamin K: A derivative of 2-methyl 1,4 napthequinone and is essential in blood-clotting mechanisms, vitamin K is found in green vegetables such as kale, spinach, cauliflower and nettles. Deficiency causes reduced activity of prothrombin resulting in haemorrhage. Henrik Dam (Denmark) and Edward Doisy (USA) were awarded the Nobel Prize for Medicine in 1943 for the discovery of vitamin K.

2.6.2 Water Soluble Vitamins

Vitamin B: Perhaps the first case of using vitamin B in treatment was in 1867 when a young Dutch doctor, Christian Eijkmann, travelled to Java to identify the cause of a mysterious illness. The illness was particularly prevalent amongst soldiers, mine-workers and prisoners which failed to respond to any kind of medical treatment. The symptoms of the illness were fatigue, paralysis and respiratory difficulties resulting in death. Dr Eijkmann called the disease beriberi which, in Singhalese, means *tired-tired*.

Dr Eijkmann noticed that chickens when fed on the leftover polished rice of those suffering from the disease began to show the same symptoms. He was quick to draw the connection between the chicken feed and the disease and was able to then prepare an extract from the husks of the rice, which he successfully used as a medicine. Christian Eijkmann was awarded the Nobel Prize for Medicine in 1929 for the discovery of the antineuritic vitamin.

Vitamin B consists of a group of related substances. For practical reasons the individual B_3 vitamins were numbered B_1, B_2, B_3, B_6 and B_{12}. The gaps in the numbering are due to other substances that scientists once (wrongly) thought were B vitamins. Three other B vitamins have a name instead of a number: pantothenic acid, biotin and folic acid.

The B vitamins each function differently. Some affect the metabolism of the cells in the body and the production of energy, while others are responsible for the formation of red blood corpuscles and DNA. The classical deficiency disease of vitamin B_3 (niacin) is pellagra, which affects the skin, digestion and nervous system. Pellagra in Latin literally means *coarse skin.* In extreme cases deficiency causes dementia and emaciation to occur and, if untreated, can be fatal.

Once a worldwide problem, pellagra was thought to have been caused either by a fungus or by bacteria. The connection between the illness and vitamin B_3 deficiency was established in 1930. Pellagra is still common in certain parts of the world today, particularly in areas where maize or millet is the staple diet.

Vitamin B_1 (Thiamin): Essential for the well-being of the nervous system and the digestion of carbohydrates in food. Thiamin is the coenzyme, which helps to break up carbohydrates. Severe deficiency leads to beriberi, a loss of muscle function as well as neurological and cardiac problems. It is found in yeast, the germ of cereals and potatoes.

Vitamin B_2 (Riboflavin): Promotes growth and healthy skin and eyes. It forms complex molecules which act as hydrogen carriers in oxidation-reduction (redox) reactions and is part of the two co-enzymes which are responsible for catalysing a series of chemical reactions necessary for energy formation in the mitochondria. The vitamin is widely distributed in foods such as liver, eggs, cheese and green vegetables. Deficiency symptoms are therefore rare although a symptom is cracking of the skin.

Vitamin B_3 (Niacin): Responsible for maintain the healthy skin and the intestinal tract vitamin B_3 is found as the co-enzyme nicotinamide adenine dinucleotide (NAD) or its phosphorylated form NADP+ which are important to the cells' energy production. Deficiency leads to pellagra. Symptoms include dermatitis, diarrhoea and mental disturbance. Occurs in food as nicotinic acid and found in yeast, meat, liver and cereals.

Vitamin B_6 (Pyridoxine): B_6 is vital for the normal breakdown of proteins in food as well as maintaining healthy skin and nervous system. Deficiency leads to epilepsy, dermatitis and anaemia.

Vitamin B_{12} (Cyanocobalamin): Like folic acid, B_{12} is important for the formation of the genetic material DNA. It is the only vitamin not to be synthesised but is instead derived from animal sources with an annual world production of around 14 tonnes of which 55% is used for animal nutrition. There are deficiency problems for people on vegan diets (no meat or fish or products of animals such as milk or eggs). A symptom of deficiency is pernicious anaemia.

Pantothenic acid: Essential for metabolism of carbohydrates, proteins, and fats, and the formation of certain hormones. Deficiency includes nervous and intestinal disorders. Widely distributed in foodstuffs.

Biotin: Produced by intestinal bacteria and important in fatty acid biosynthesis and gluconeogenesis. It is essential to many chemical systems in the body. Deficiency rarely occurs although symptoms include dermatitis and loss of hair. This is sometimes referred to as B_8 or vitamin H.

Folic acid: Important for synthesis of the component comprising the genetic material DNA. It is recommended that expectant mothers supplement their diets in the early stages of pregnancy. It is also vital for the correct functioning of the blood-forming organs. Deficiency symptoms are intestinal disorders and anaemia.

Vitamin C: Scurvy is a vitamin-deficiency disease brought on by a lack of fresh vegetables and fruit and was once a widespread and fatal disease. For centuries, the dreaded disease plagued seafarers on long sea voyages. When the fifteenth century Portuguese mariner Vasco da Gama opened up a sea route to India by sailing around the Cape of Good Hope, 100 of his crew of 160 died from the illness. The Portuguese-born explorer Ferdinand Magellan - born in 1480 and known as the greatest explorer of his age - was also no newcomer to the appalling disease. A member of one of his expeditions wrote in his chronicle, "We were three months and twenty days without getting any kind of fresh food. We ate biscuits which was no longer biscuit but powder of biscuits swarming with worms", adding, "The gums of both the lower and upper teeth of some of our men swelled, so that they could not eat under any circumstances and therefore died."

Over two centuries later, in 1747, the Scottish naval surgeon Dr James Lind performed an experiment on a group of sailors suffering from scurvy. Dr Lind showed that by taking a daily supplement of oranges and lemons the disease could be prevented from occurring. His claims were met with much scepticism and disbelief. British maritime explorer Captain James Cook, however, was quick to realise the value of a diet of fresh fruit and vegetables on long sea voyages and was almost militant in enforcing dietary rules to prevent scurvy amongst his crews. In spite of Captain Cook's success in his battle against the disease, it took a further fifty years for the British Admiralty to prescribe a daily ration of lemon juice for all sailors in the Navy. By the beginning of the 19th century scurvy was no longer a threat to the British fleet.

Even though citrus fruits were known to have prevented scurvy, it was not until the Hungarian Nobel Prize winner for Medicine Albert Szent-Györgyi (1937) successfully isolated the vitamin. He named it ascorbic acid as an abbreviation of *anti-scorbutus*, which is Latin for *against scurvy*.

Ascorbic acid has many important roles in the body and is particularly concerned with the growth and repair of body cells and tissue helping to fight infection, and with the absorption of iron from food. Iron is required in the manufacture of haemoglobin; the red pigment in the blood which transports the vital oxygen from the lungs to the rest of the body. The vitamin is also important for the formation of the protein collagen, which strengthens the cells that build up bones.

A severe deficiency leads to scurvy which causes bleeding in the skin and joints, around the bones and from gums and can lead to death. Potatoes, green vegetables and citrus fruits such as oranges and lemons are the commonest sources and blackcurrant and rosehip extracts are particularly rich.

Dietary studies have shown that by eating large quantities of fresh fruit and vegetables that are rich in vitamin C the risk of contracting certain diseases reduces. There are also claims that high doses of vitamin C can help fight cancer cells. There are no studies, however, that unequivocally support this claim.

Taking large quantities of vitamin C in tablet form over a long period of time can cause a risk of kidney stones; the excess vitamin is turned into oxalate which, when combined with calcium, is transformed into kidney stones.

2.6.3 Vitamin Loss

Vitamins in fruit and vegetables may be destroyed or lost in several ways between harvesting and consumption. The water-soluble vitamins of the B-complex and vitamin C tend to be more unstable during cooking and processing than the fat-soluble vitamins (Table 2.6). In addition, both water-soluble vitamins and minerals may be lost by diffusion from the food into the cooking medium. In some cases these nutrients may still be consumed, as the cooking water may be used for making sauces or gravy. Similarly, the liquid syrup from canned fruit is normally consumed, but in many cases the cooking water is discarded.

Table 2.6 Stability of Water-Soluble Vitamins during Cooking and Processing

Vitamin	*Alkaline*	*Neutral*	*Acid*	*UV-light*
Thiamin, B_1	unstable	unstable	stable	stable
Ribflavin, B_2	unstable	stable	stable	unstable
Niacin, B_3	stable	stable	stable	stable
Pyridoxine, B_6	stable	stable	stable	stable
Cyanocobalamin, B_{12}	unstable	stable	stable	stable
Folic acid	unstable	unstable	stable	stable
Pantothenic acid	unstable	stable	unstable	stable
Ascorbic acid, C	unstable	unstable	unstable	unstable

The fat-soluble vitamins are more stable than the water-soluble vitamins under normal conditions. Vitamin D is completely stable; both vitamin A and carotene, from which it can be derived, are stable below 100°C. However, both forms suffer losses during frying, exposure to sunlight, dehydration and during the storage of dehydrated food.

The tocopherols (vitamin E) are natural antioxidants, but in protecting fats and vitamin from oxidation during storage, cooking and processing are themselves oxidised. The most unstable fat-soluble vitamin is vitamin K, which is destroyed in the presence of acids, alkalis, oxidising agents or sunlight and by prolonged heating.

The exact amount of vitamins lost during boiling of vegetables depends on the type of vegetables being boiled (Tables 2.7, 2.8 and 2.9).

Table 2.7 Vitamin Loss (%) During Boiling of Vegetables

Vegetable Type	B_1	B_2	B_3	C	Folic acid
Leafy	40	40	40	70	70-100
Seeds & Fruit	30	30	30	50	70-100
Roots	25	30	30	40	70-100

Table 2.8 Thiamin Loss (%) in Cooked Meats

Meat	*Cooking Method*	*Loss (%)*
Beef	Roast	40-60
	Stewed	50
	Fried	0-45
	Canned	80
Pork	Roast	30-40
Ham	Baked	50
	Fried	50
	Canned	50-60
Bacon	Fried	80
Poultry	Roast	30-45
Fish	Fried	40

Table 2.9 Vitamin C Loss (%) in Juices (After 12 Months of Processing)

Beverage	*Vit. C Remaining (%)*
Carbonated juice	54-64
Apple juice	58-74
Cranberry juice	78-83
Grapefruit juice	73-86
Pineapple juice	74-82
Tomato juice	64-93
Vegetable juice	66-69
Grape drink	65-94
Orange drink	75-83
Evaporated milk	70-82

Example

A series of experiments were conducted to determine the rate of degradation of vitamin C in processed orange juice. If the degradation follows first order kinetics, determine the rate constant.

Time (mins)	Vitamin C (mg per 100 mL)
0	47
10	38
20	31
30	25

Solution:

The first order reaction is given by

$$\frac{dV}{dt} = -kV$$

Rearranging, the amount of vitamin C remaining, V, at time t is

$$-k\int_0^t dt = \int_{V_o}^{V}\frac{dV}{V}$$

Integrating and rearranging

$$kt = \ln\left[\frac{V_o}{V}\right]$$

For the date provided:

$$k = \frac{\ln\left[\frac{47}{38}\right]}{10} = 0.021s^{-1}$$

$$k = \frac{\ln\left[\frac{47}{31}\right]}{20} = 0.021s^{-1}$$

$$k = \frac{\ln\left[\frac{47}{38}\right]}{10} = 0.021s^{-1}$$

The consistency of the rate constant confirms first order kinetics.

2.6.4 Macro Minerals

Calcium: Required for hard bones, transmission of nerve impulses, activates certain enzymes, necessary for maintenance of membrane potential and muscle contraction. 99% in skeleton, remainder in extracellular fluids, intracellular structures and cell membranes.

Men's RDA	15-24 years-1200mg	25-50 years - 800mg
Woman's RDA	15-24 years-1200mg	25-50 years - 800mg

Found in dairy products, sardines, clams, oysters, turnip/mustard greens, broccoli and legumes. Excess leads to constipation, hypocalcaemia, kidney stones. High levels may inhibit intestinal absorption of iron, zinc, other nutrients. Deficiency leads to risk of bone injury and osteoporosis, especially in females.

Magnesium: Co-factor of enzymes in energy metabolism, maintenance of electrical potentials in muscles and nerves, component of bone. Most found in muscles and soft tissue, 1% in extracellular fluid, remainder in skeleton.

Men's RDA	15-18 years - 400mg	19-50 years - 350mg
Woman's RDA	15-18 years - 300mg	19-50 years - 280mg

Found in nuts, legumes, unmilled grains, soybeans, chocolate, corn, peas, carrots, seafood, brown rice and lima beans. Excess leads to nausea and vomiting. Deficiency is rare and leads to muscle weakness.

Phosphorus: Component of bone, buffer in body fluids, component of ATP, nucleotides and co-enzymes. 85% in skeleton, remainder in soft tissue and blood.

Men's RDA	15-24 years -1200mg	25-50 years - 800mg
Woman's RDA	15-24 years-1200mg	25-50 years - 800mg

Found in protein-rich food, milk, meat, poultry, fish, eggs, nuts, legumes, cereals. Excess leads to lowering of blood calcium. Deficiency is rare.

2.6.5 Trace Minerals

Zinc: Co-factor of several enzymes in energy metabolism, immune function, possible anti-oxidant, wound healing, taste and smell. Found in bones and muscle, liver, kidney and brain.

Male RDA	15-50 years - 15mg
Woman's RDA	15-50 years - 12mg

Found in oysters, wheat germ, beef, calf liver, dark meat in poultry and whole grains. Excess leads to gastro-intestinal irritation, impaired copper absorption and reduction in high-density lipoproteins. Deficiency leads to appetite loss, poor wound healing, abnormal taste and smell, changes in hair and skin.

Copper: Required for proper use of iron, role in development of connective tissue, co-factor to oxidases. Found in liver, heart, kidney, spleen and brain.

Male RDA	11+ years -1.5-2.5mg	Adult - 1.5-3.0mg
Woman's RDA	11+ years -1.5-2.5mg	Adult - 1.5-3.0mg

Found is organ meats, shellfish, whole grains, legumes, chocolate and nuts. Excess is rare but is potentially toxic. Deficiency is rare leading to anaemia.

Selenium: Anti-oxidant, co-factor of glutathione peroxidase. Stored in liver and kidneys.

Men's RDA	15-18 years - 50µg	19-50 years-70µg
Woman's RDA	15-18 years - 50µg	19-50 years-55µg

Found in grains, meat, poultry, fish, dairy products. Excess is not known although hair loss, nausea and diarrhoea are possible. Deficiency is not known although myalgia and cardiac myopathy are possible.

Chromium: Enhances effectiveness of insulin.

Men's RDA	11+ years - 50-200µg
Woman's RDA	11+ years - 50-200µg

Found in mushrooms, prunes, nuts, asparagus, organ meats, whole grain bread and cereals. Excess is not known. Deficiency is not known although impaired glucose tolerance anaemia is possible.

Iron: Necessary component of haemoglobin, myoglobin transport of oxygen, facilitates transfer of electrons in electron transport system. 60-70% found in haemoglobin with the remainder in bone marrow, muscle, liver and spleen.

Men's RDA	15-18 years-12mg	19-50 years-10mg
Woman's RDA	15-50 years-15mg	

Found in meats, black strap molasses, clams, oysters, dried legumes, nuts and seeds, red meats, dark green leafy vegetables. Excess is rare causing liver damage. Deficiency leads to anaemia and fatigue.

2.7 Flavours and Aromas

The term "flavour" is used to describe the quality of food but it is neither very well defined nor properly understood. In fact, flavour describes the complex and interacting set of sensations experienced when food is consumed. Flavour is a distinctive taste and savour and may be defined as "that quality of something which affects the sense of taste or gratifies the palate: savour is the blend of taste according to smell sensations evoked in a substance in the mouth."

Flavour is a subtle combination of the four distinguishable elements of sweetness, sourness, bitterness and saltiness. In recent years, a fifth distinguishable flavour has become accepted. It is best known in the form of monosodium glutamate (MSG). The Japanese named this new taste *umami*, which means roughly "savoury" in English.

Natural products contain many aroma chemicals. Tarragon essential oil, for example, contains up to 77 components and coffee over 800. Others, on the other hand, contain fewer major components. Vanilla, for example, contains the major ingredient vanillin, which was first synthesized in 1874. Whilst some synthetic flavourings are prepared by using such major components as the key ingredient, the majority are complex mixtures of the many important aroma chemicals found in nature.

Many flavours are the result of specific chemical processes such as fermentation (cheese, yogurt, alcoholic drinks) or roasting and frying (meat, chocolate, toast, deep-fat-fried food). Fermentation, roasting and toasting create specific chemical reactions in foods. The sweet caramelly taste of fried onions, gravy, or the crackling on pork involves a chemical reaction between proteins and carbohydrates in a non-enzymatic brown reaction first discovered by the French chemist, L.C. Maillard, in 1912.

Variations on the browning reaction produce many of the most desirable flavours. Examples include allylpyrazine which gives a roasted nut-like flavour; methoxypyrazines earthy vegetables; 2-isobutyl-3 methoxypyrazine gives green pepper, and acetyl-l-pyrazines popcorn; 2-acetoxy pyrazine produces toasted flavours. During World War II two scientists, H.M. Barnes and C.W. Kaufman, discovered that the reactions between sugars and proteins could produce not only the off-flavours but also desirable flavours. In 1947 a maple syrup flavour was patented as the first Maillard reaction flavour.

Flavours are additives that create or improve flavours and many, depending on the strength of the flavour desired, range from 0.01% to 2%. The usage in foods can correspondingly range from a few kilogrammes per year to several thousand tonnes. These may be either natural (ie obtained from plant or animal sources), natural identical (ie chemically synthesised but chemically identical) or artificial (ie not produced in plants or animals).

Alcohols, aldehydes, ketones, esters and lactones are classes of compounds that occur most frequently in nature and artificial flavours. The majority of flavours have molecular masses of around 200 and are rarely above 300.

Table 2.10 Examples of Synthesised Flavours:

Type	Name	Formula	m_w	bp (°C)	Aroma
Ketone	3-hydroxy-2-butanone (Acetoin)	$C_4H_8O_2$	88	148	Butter
Ketone	1-(4-hydroxyphenyl)-3-butanone	$C_{10}H_{12}O_2$	164	83	Raspberry
Ester	Isoamyl acetate	$C_7H_{14}O_2$	130	142	Banana
Ester	Ethyl acetate	$C_4H_8O_2$	88	77	Brandy
Ester	Ethyl butyrate	$C_6H_{12}O_2$	116	122	Pineapple
Aldehyde	Hexanal	$C_6H_{12}O$	100	128	Unripe fruit
Lactone	δ Decalactone	$C_{10}H_{18}O_2$	170	156	Peach
Lactone	γ Decalactone	$C_{10}H_{18}O_2$	170	120	Coconut

Example:

Ethyl ethanoate, b.p. 88°C, has the characteristic aroma of brandy and can be made by condensing together ethanol, b.p.78.5°C, and ethanoic acid, b.p. 118°C. The reaction is reversible. Write a balanced equation for the formation of ethyl ethanoate from ethanol and ethanoic acid. Suggest a way in which the rate of reaction can be increased and why distillation is not a suitable process for purifying the ester.

Solution:

$$CH_3COOH + C_2H_5OH \Leftrightarrow CH_3COOC_2H_5 + H_2O$$

The reaction can be promoted by the addition of a suitable acid. Distillation is not suitable since ethanol has the lowest boiling point and therefore drives the reaction in favour of the reactants and not the products.

Example:

The hydrolysis of a favour ester can be catalysed by hydrochloric acid for which, at a given temperature, the pseudo first order reactions with added acid are shown.

$Conc^n.\ HCl$ / $mol.dm^{-3}$	k / s^{-1}
0.025	2.75×10^{-5}
0.050	5.5×10^{-5}
0.100	1.1×10^{-4}

Determine the catalytic coefficient if the reaction rate can be related to the amount of catalyst by

$$k = k_{cat}[catalyst]$$

Solution:

$$k_{cat} = \frac{k}{[catalyst]}$$

For the three concentrations

$$k_{cat} = \frac{2.75 \times 10^{-5}}{0.025} 0.0011 mol.dm^{-3}.s^{-1}$$
$$k_{cat} = \frac{5.5 \times 10^{-5}}{0.050} 0.0011 mol.dm^{-3}.s^{-1}$$
$$k_{cat} = \frac{1.1 \times 10^{-4}}{0.100} 0.0011 mol.dm^{-3}.s^{-1}$$

Thereby concluding that the pseudo first order reaction applies.

2.8 Additives and Antioxidants

The European Food Safety Authority (EFSA) is the keystone of European Union (EU) risk assessment regarding food safety working in close collaboration with national authorities has produced a list of permissible food additives. The so-called E-numbers are a systematic way of identifying different food additives. The E-number is only given to an additive that has passed all the necessary food safety checks.

Many food additives are anti-oxidants and used to preserve or enhance certain foods. All foodstuffs are vulnerable to oxidation. The most familiar examples are the browning of cut apples or potatoes when exposed to air. The use of lemon juice demonstrates the principle of anti-oxidation since lemon juice contains vitamin C (E300), which is one of the most potent antioxidants.

Atmospheric oxygen is not the only oxidizing agent. It is combined in the form of oxides and peroxides in atmospheric pollution, cigarette smoke and in some normal bodily processes. Oxidation can cause breaks in DNA (and hence the risk of cancers), oxidise polyunsaturated fatty acids, and thus contribute towards heart disease and strokes and can damage proteins. The proteins in the eye are particularly vulnerable because light also assists the oxidation process. Increasing the intake of antioxidants has a preventative effect against both cancer and heart disease. The oxidation of lipids is one factor in the development of heart disease.

Besides all their other advantages, antioxidants confer huge economic and environmental benefits in preventing wastage of food.

Acids are a major component of natural foods. Zest is a highly desirable attribute in food, and sharpness of flavour is always due to acids. Phosphoric acid (E338) gives the sharpness in cola drinks. All fruits contain characteristic acids such as citric in lemons, malic in apples, tartaric in grapes. The acids that are added to food are all, except phosphoric acid, found in natural foodstuffs. Besides imparting sharpness of flavour, acids are used because the overall acidity of foods can be crucial.

Acids also have preservative and antioxidant properties. In jam-making the acidity of the fruit determines its setting properties The most commonly used acid is citric acid (E330). Originally derived from citrus fruits it is now produced by fermentation of molasses by an aspergillus mould. Besides adding tartness, it is also an antioxidant and a preservative. Phosphoric acid (E338) is the next most commonly used acid.

3 Food Processing Operations

3.1 Introduction

The main processes used to produce foods of satisfactory biological standards and acceptable eating quality, are mechanical processes, heating, cooling, the use of additives, and fermentation processes. Each of these has a range of effects on the organoleptic properties of food. Recent developments in food processing methods include aseptic processing, irradiation (non-thermal), pulsed electric fields (non-thermal) and high pressure processing (non-thermal).

3.2 Mechanical Processes

Many raw food materials undergo a preliminary treatment by a mechanical process. Many first involve size reduction such as cutting into smaller pieces such as potatoes into small chips before frying. Size reduction processes can, however, involve injury to living cells and may therefore affect the appearance of the foodstuff in undesirable ways.

In some fruit and vegetables, enzymatic browning may occur. The grey-black discolouration found in cut potatoes and the brown discolouration found in cut apples is due to the action of the enzyme polyphenoloxidase (PPO) on phenolic compounds or tannins. These substances are normally colourless in intact living plant tissue. When cells are damaged by bruising or cutting during the preparation of food, the phenolic compounds are oxidised forming brown or black grey polymers. PPO is present in apricots, cherries, pears, bananas, avocados and sweet potatoes.

A similar enzyme reaction can occur between the vitamin C in fruits and the enzyme ascorbic acid oxidase. Such enzymatic reactions can be prevented or reduced several ways:

- Chilling reduces enzymatic reaction rates
- Lowering pH to below 2.5 inhibits enzyme activity
- Additives inhibit enzyme activity such as the use sodium metabisulphate, salt, sugar, potassium phosphate and ascorbic acid
- Heat inactivates enzyme activity such as the use of blanching
- Complete exclusion of air (oxygen) prevents oxidative reactions

Other mechanical treatments of foods include filtration and centrifugation, which are used to separate fluids from solids, or from liquids of different density. In a cream separator, less dense fat globules are separated from the water and dissolved lactose and proteins of milk.

The final form of mechanical treatment is protective packaging. This is a physical barrier such as a can, jar or plastic sachet, for protection against spoilage, organisms, dirt, and mechanical damage. Packaging technologies are classified into either modified atmosphere packaging (MAP) or controlled atmosphere packaging (CAP).

3.2.1 Raw Material Preparation

The objective of raw material preparation is the removal and separation of contaminating materials from the food in order to attain a suitable condition for further processing. Contaminants may be soil, micro-organisms and pesticide residues. Washing is widely applied as a first processing step to root crops, potatoes, fruits and vegetables. Soaking is predominantly applied to the processing of legume seeds.

Large volumes of water are often required for washing root vegetables, which carry a lot of soil, and also for leafy vegetables, which have a large surface area. Mechanical or air flotation techniques are used to assist soil removal and reduce the quantity of water used. Water re-circulation or re-use from other food process operations is commonly used. Waste water from pre-washing mainly contains field debris and soil particles with small fragments of the fruit or vegetable. Detergents can increase cleaning efficiency but also contribute to the chemical oxygen demand (COD) of the waste water.

Washing is carried out by vigorous spraying with water, which may be chlorinated, and by immersion, with the aid of brushes or by shaking and stirring. Surface active agents and warm water are sometimes used. The use of warm water, however, can increase both the chemical and microbiological spoilage, unless careful control on the washing process is carried out. Once loosened, soil can be separated and recovered by sedimentation.

The soaking of legume seeds in water varies with variety and species and with the duration and conditions of storage. Dry beans can be soaked in cold water for between 8 and 16 hours while high temperature soaking increases the rate of hydration.

Dry cleaning procedures are used for products which have a low moisture content and high mechanical strength such as nuts and grains. Typical equipment used includes air classifiers, magnetic separators, sieving and screening.

Most raw materials for processing may contain contaminants; have inedible components or irregular physical characteristics. Processing techniques such as sorting, grading, screening, de-hulling and trimming are therefore necessary to reach uniformity prior to further processing.

Sorting and screening are used to separate raw materials into categories on the basis of shape, size, weight and colour. In size-sorting, solids are separated into two or more fractions by sieving and screening. Size-sorting is important where over or under-sized material may lead to over of under cooking or cooling. Various types of screens and sieves, with fixed or variable apertures, are used while screens may be stationary, rotary or vibrating.

Shape-sorting is carried out either manually or mechanically such as with belt-and-roller sorters. Weight-sorting is used for more valuable foods such as cut meats, eggs, exotic fruits and vegetables. Image-processing is used to sort foods on the basis of length, diameter, number of surface defects and orientation of food on a conveyor. The images of the surface are digitally recorded by a digital camera or sensor and the data compared with pre-programmed specifications. Colour-sorting uses photo detectors to record reflected colour and compared with pre-set standards. Products are then either rejected by blasting away the compressed air or can be moved into a group with similar characteristics.

Grading is the assessment of a number of characteristics of a food to obtain an indication of the overall quality of a particular food. It is mainly carried out by trained operators. Fish and meats are all examined by inspectors for disease, fat distribution, size and shape. Other graded foods include cheese and tea. Grading is more expensive than sorting due to the high costs of skilled personnel. Trained operators have the benefit of being able to assess many characteristics simultaneously.

Trimming involves the removal of inedible parts or parts with defects and cutting to a size appropriate for further processing. It usually is carried out manually or by rotating knives.

Many vegetables and some fruits require peeling. Peeling can be achieved by mechanical cutting or abrasion, or by the application of steam, hot water or heated air. The use of caustic in peeling involves a dilute solution of sodium hydroxide and is used to soften the cortex so that the peel can be more easily removed by mechanical scrubbers or high pressure water sprays. This also removes any residual caustic and may lead to pH fluctuations in the waste water. Certain fruit such as tomatoes requires strong caustic solutions and the addition of wetting agents.

Flash steam peeling is carried out as a batch process. Roots and tubers are treated in a pressure vessel and exposed to steam at a pressure of up to 20 bar. The high temperature causes a rapid heating and cooking of the surface layer within 15 to 30 seconds. The pressure is then instantly released which causes flashing-off of the cooked skin. Remaining traces are sprayed off with water.

In knife peeling, fruits and vegetables to be peeled are pressed against stationary or rotating blades to remove the skin. Knife peeling is used for citrus fruits where the skin is easily removed causing little damage.

In abrasion peeling, the material is fed onto carborundum rollers or fed into a rotating bowl, which is lined with carborundum. The abrasive carborundum surface removes the skin, which is then washed away with water. Normally carried out normally at ambient temperature, this has a significantly higher product loss than flash steam peeling.

Developed for onions, a flame peeler consists of a conveyer belt which transports and rotates the onion through a furnace heated to temperatures in excess of 1000°C. The skin, which consists of a paper shell and root hairs, is rapidly burnt off. The skin is removed by high-pressure water sprays.

Grinding and milling are used for size reduction of solid dry material and used extensively in the flour milling, brewery, sugar and dairy industries. Various techniques and equipment are used for specific types of food for both dry and wet applications. In wet processes, smaller particle sizes can be attained while dry processes combined with sieving or air classification permits the collection of a particle size range. The common types of mill used in food industry include:

Hammer mills: The mill consists of a horizontal cylindrical chamber lined with a steel breaker plate. Hammers along its length disintegrate the material by impact force.

Ball mills: The mill consists of a slowly rotating, horizontal steel cylinder, half filled with steel balls between 2.5 and 15 cm in diameter. The particle size attained depends on the speed and size of the balls.

The purpose of cutting, slicing, chopping and pulping is to reduce the size of fibrous material usually to improve the eating quality or produce foods for further processing. These activities are applied in processing of meat, fish, cheese, vegetables, fruits, potatoes, and various other crops. Slicing equipment consists of rotating or reciprocating blades. The material may be pressed against the blades by centrifugal force. For slicing meat products, the material is held firm while it travels across the blade. Harder fruits such as apples are simultaneously sliced and decored.

Dicing is applied to vegetables, fruits and meats in which the material is first sliced and then cut into strips by rotating blades. These are then fed to a second set of rotating knives, which operate perpendicular to the first set and reduce the strips into cubes.

Many products such as meat, fish and vegetables require reducing to small particles. Mincing is mainly used for size reduction and homogenisation. In bowl chopping, material is placed in a slowly rotating bowl and subjected it to a set of blades rotating at high speed. This technique is widely used in the production of sausages in which the degree of comminution can be varied depending on knife-speed and cutting time. In extreme cases the material will be reduced to an emulsion.

3.2.2 Forming, Moulding and Extrusion

Forming, moulding and extruding are widely applied for the production of bread, biscuits, cheese, confectionery and pies. In forming and moulding, the material is prepared as a soft mixture which firms on processing such a baking.

Extrusion is widely used for the production of meat sausages, pasta products such as spaghetti and starch-based snack food. As a continuous process of shaping, the material is kneaded under high pressure and pressed continuously through openings of the required shape using the action of rotating screws. In cooking extruders, the material is also heat treated or cooked to solublise the starches.

3.3 Heating

As well as destroying pathogens and other spoilage organisms, heating is used to improve food palatability. Heating also provides a rapid means of removing moisture and as well as producing a number of physical and chemical changes.

3.3.1 Steam and Water Heating

Blanching is an important step in processing of fruits and green vegetables and involves their exposure to high temperatures for a short period of time. The primary function of blanching is to inactivate or retard surface bacterial and enzyme action, which causes rapid degeneration of quality. Blanching is also able to expel air and other gases from products.

Blanching may be carried out either by immersion in hot water (80°C to 100°C) or exposure to live steam depending on the fruit or vegetable to be blanched. The residence time in the blancher can vary from approximately one second to five minutes depending on the fruit or vegetable being blanched.

3.3.2 Evaporation

Evaporation is the partial removal of water from liquid food by boiling. Evaporation is used to pre-concentrate, increase the solid content and to change the colour of food. It is used to process milk, starch, coffee, fruit juices, vegetable pastes and concentrates, seasonings, sauces as well as sugar processing.

Steam or vapour is usually used as the heating medium, the latent heat of condensation is used to raise the temperature to the boiling point of the liquid food causing evaporation of the water. Since many liquid food products are heat sensitive it is often necessary to work at reduced temperatures. This is achieved by boiling under part vacuum. Evaporation occurs normally between 50°C to 100°C.

The most commonly used equipment consist shell and tube evaporators which are either climbing or falling film types. Wiped film evaporators and thin film evaporators are used for the evaporation of highly viscous products.

For large-scale evaporation requiring significant energy such as the processing of sugar beet or evaporation of milk and whey, multiple-effect evaporators are used. These use fresh steam to boil off water vapour from the liquid in the first effect. The evaporated water retains sufficient energy to be used as the heat source for the next effect, and so on. A vacuum is applied in a ple effect chain in order for the water to boil off. The liquid food is passed from one evaporator effect through the others so that it is subject to multiple stages of evaporation.

3.3.3 Pasteurisation, Sterilisation and UHT

The treatment of foods by heat is principally used in their preservation. It prevents bacterial and enzyme activity otherwise resulting in the loss of product quality. Various temperature-time combinations can be applied with each depending on product properties and shelf life requirements. For complete sterilisation, the product is canned or bottled and then heat-treated in a retort in hot water or steam in either a batch or continuous operation.

In pasteurisation, a heating temperature below 100°C is applied. This results in a partial reduction of the enzyme and bacterial activity within a product giving a limited shelf life. Sterilisation commonly means a heat treatment in excess of 100°C to achieve a stable and extended shelf life.

Ultra high temperature (UHT) processing uses a temperature exceeding 135°C for very short times. It is applied to low viscosity liquid products. This uses indirect heating in plate and frame or tubular heat exchangers. Direct steam injection or steam infusion can alternatively be used.

Batch wise pasteurisation is carried out in agitated vessels. For beer and fruit juices, pasteurisation is applied after bottling or canning. The packaged products are immersed in hot water or led through a steam tunnel. For continuous pasteurisation flow-through tubular or plate and frame heat exchangers with heating, holding and cooling sections are used.

3.3.4 Hot Air

Baking and roasting are forms of hot air heating involving both convective and radiative heat transfer. Baking is used to improve eating quality by way of taste and texture of a food. It is also a means of preservation by the destruction of micro-organisms and reduction of water activity at the surface of the food. The shelf life of most baked foods, however, is limited, unless they are refrigerated or packaged.

Operating either batch or continuously, baking is applied on a large scale to flour-based products such as bread and bakery products as well as to fruit and vegetables. Baked products include pies, pizza and snack foods. In the baking process, the moisture at the surface is evaporated and removed by circulating hot air. When the rate of moisture loss at the surface exceeds the rate of transport of moisture from the interior of the product to the surface, the surface dries out forming a crust.

The purpose of roasting is to dry and enhance the aroma as well as structure of the food product. Typical roasted products include coffee, cereals, nuts, cacao and fruits. In roasting, water contained within the product is evaporated and the moisture content may fall to below 1%. At temperatures exceeding 120°C chemical reactions may take place in the product. Maillard reactions (see 2.3) are particularly important in the formation of aromas in coffee and cacao. The duration of the roasting process is dependent on the product and the specific aromas that are required. The roasting of coffee may range from one to twenty minutes. The Maillard reactions are stopped either by cooling the product with air or by quenching with water followed by cooling with air.

As with baking, roasting ovens can operate either batch or continuously. Typical equipment for batch roasting ovens includes drum, column, rotating or fluidised bed roasters. In each, the product is heated and agitated simultaneously. The product can be in direct contact with the hot convective air or in contact with a heated conductive surface. In practice, it is usually a combination of both.

In drying and dehydration processes, the shelf life of foods is extended by the reduction of water activity. Typical applications include milk, coffee, tea, flavours, powdered drinks and sugar. In hot air drying, the heat transferred from the air to the product causes water evaporation. The main types of hot air dryers include bin, tray, tunnel, conveyor or belt, fluidised bed, kiln, pneumatic, rotary and spray dryers.

In fluidised bed dryers, there is good thermal control over the drying conditions. They have very high rates of heat and mass transfer and consequently short drying times. Drying can take place below 100°C.

3.3.5 Hot Oil

Frying involves cooking food in edible oil at temperatures in the region of 200°C. Vegetable oils are normally used. Raw material such as fish, meat and potatoes can be fried to produce products such as fish fingers, burgers and French fries.

Frying may be either batch or continuous. In continuous frying, the chamber contains the heated oil. A belt feeds the product into the main fryer belt and controls the frying time. The take-out belt at the end of the fryer lifts the product out of the oil, allowing the product to drain and transfer onto product inspection and packing belts. The residence time in the fryer can range from 30 seconds to 6 minutes depending on the product.

3.3.6 Heat Removal

Cooling and Chilling: The purpose of cooling and chilling is the reduction of the rate of biochemical and microbiological change, in order to extend the shelf life of fresh and processed foods. Cooling involves reducing the temperature of the food from the processing to the storage temperature. Chilling involves maintaining the temperature of a food at a temperature of between -1^{o}C and 8^{o}C.

The cooling of liquid foods is typically carried out by passing it through a heat exchanger which is cooled using water. In cryogenic cooling, the food is in direct contact with a refrigerant, which can be either solid, liquid carbon dioxide or liquid nitrogen. Refrigerant boiling, evaporation or sublimation removes the heat from the food causing rapid cooling.

Freezing: Freezing is a method of preservation where the temperature of a food is reduced below its freezing point and a proportion of the water undergoes a change in state to form ice crystals. Several types of food can be frozen including fruit, vegetables, fish, meat, baked products and ice cream. The equipment for freezing foods includes blast, belt, fluidised bed, cooled surface, immersion and cryogenic freezers.

In freeze-drying or lyophilisation, water is removed through sublimation and desorption. The aim is to preserve sensitive material that can not be dried by evaporation at elevated temperature because of the sensitivity to degradation of specific components at high temperature resulting is loss of taste or other quality aspects. The technique is typically used for drying coffee extract, spices, soup vegetables, instant meals, fish and meat. Typical lyophilisation equipment consists of a drying chamber with temperature controlled shelves. The chamber is cooled by refrigerant through the shelves and the chamber itself is under vacuum. A condenser is used to trap water removed from the product in the drying chamber and facilitate the drying process.

Example:

There is a 50% destruction of a vitamin at 115^{o}C in 15 minutes where, for the vitamin, E is 109 kJ.mol^{-1}. Determine the extent of the vitamin destruction at 120^{o}C after 15 minutes of processing.

Solution:

At the temperatures considered, the thermal destruction of a heat labile vitamin can be said to follow a simple first order reaction:

$$\frac{dV}{dt} = -kV$$

Thus the amount of vitamin remaining, x, is at time t is therefore

$$-k\int_0^t dt = \int_1^x \frac{dV}{V}$$

Integrating gives

$$kt = \ln\left[\frac{1}{x}\right]$$

The thermal destruction is dependent on temperature and can be given by the Arrhenius equation:

$$k = Ae^{\frac{-E}{RT}}$$

Assuming a first order model then the rate constant is

$$k_{115^oC} = \frac{\ln\left(\frac{1}{0.5}\right)}{15} = 0.046\,\text{min}^{-1}$$

From the Arrhenius formula

$$A = \frac{k_{115^oC}}{e^{\frac{-E}{RT}}} = \frac{0.046}{e^{\frac{-109000}{8.314\times(273+115)}}} = 2.174\times10^{13}$$

The rate constant at 120°C is therefore

$$k_{120^oC} = A\times e^{\frac{-109000}{8.314\times(273+120)}} = 0.0707\,\text{min}^{-1}$$

The fraction of vitamin remaining is therefore

$$x = e^{-kt} = e^{-0.0707\times15} = 0.346$$

That is, a 65% destruction of the vitamin. This result corresponds to a fixed temperature. In reality, there will be a period of heating which will correspond to an accumulative loss of the vitamin, which will slow again on cooling. The overall effect for a period of heating and cooling can be calculated using increments of time and accumulating the loss of vitamin.

3.4 Mixtures and Emulsions

Most foods are prepared and consumed as mixtures. Mixing is essential to encourage certain desirable reactions to occur between the constituents and various emulsions. This may involve the bringing together of dry, free-flowing solids through to complex viscous liquids, slurries, pastes and doughs. Agitation of these materials involves many complex interfaces and free surfaces. The flow properties of the components and those of the mixture at any point during mixing are both complex and time-dependent.

Emulsification occurs when two liquids which are not soluble in one another are dispersed into fine droplets within each other. Water-in-oil emulsions, such as butter, consist of very fine droplets of water containing dissolved salts, lactose and lactic acid are dispersed throughout the butter fat or oil phase. Oil-in-water emulsions, such as mayonnaise consists of minute droplets of a vegetable oil are dispersed in an aqueous solution of vinegar.

To prevent liquids in an emulsion from separating into two layers, an emulsifying agent is used. Egg yolk, which contains a lecithoprotein, is used as the emulsifying agent, and prevents the droplets of oil from coalescing. This is due to the structure of lecithoprotein which comprises two parts; a hydrophilic (water-loving) protein and hydrophobic (water-repelling) protein, which is attracted to lipid materials such as vegetable oil.

Mixing is one of the most commonly encountered operations in the food industry. As a blending process, it involves the combination of different materials and their spatial distribution until a certain degree of homogeneity is achieved. Various mixing operations can be distinguished.

Solid/solid mixing: Used for mixed feed, blends of tea and coffee, dried soup, cake mixes, custard, ice cream.
Solid/liquid mixing: Used for canned products, dough, dairy products
Liquid/gas mixing: Used for making ice cream, whipping cream.

A wide variety of food mixers are available with equally wide-ranging capabilities. Some are designed for specific applications such as emulsification or solid dispersion into liquids. Others tend to be required to carry out various duties. The design of most mixers is rarely based on theoretical considerations. Instead, design is often based on past experience.

The dispersion of food ingredients by the agitator may require high levels of shear as in the case of making fine dispersions and emulsions while the mixing of nuts into yoghurt, on the other hand, may require low shear. Many foods contain particles of different sizes, some of which are fragile. These particles may have to be dispersed into viscous liquids such as a sauce. It is therefore difficult to produce a uniform product composition in which particle segregation is often a problem.

Regardless of the shape or size of the mixer, its design features must ensure hygienic and safe operation, as well as provide for in-place cleaning. Mixers used in the food processing industries may be conveniently classified according to the materials to be mixed as dissolving and dispersion of liquids, blending of particulate material and mixing of solids and liquids to form doughs, batters and pastes.

3.4.1 Emulsification

Emulsification of foods is one of the most complicated unit operations since the nature of the final product is dependent on the method of preparation. Even the method of addition of components and the rate of addition can significantly affect the emulsion quality. Oil-in-water emulsions are widely used and may be produced in impeller-agitated vessels operating at high rotational speeds, colloidal mills or high-pressure valve homogenisers. Continuous processing may be achieved by in-line mixers, which consists of a high-speed rotor inside a casing into which the components are pumped and subjected to high shear. Emulsions are formed under extremely high specific power.

3.4.2 Mixer Performance

The performance of mixers in the food industry is typically expressed in terms of fluid velocity generated, total pumping capacity of the impeller, and total flow in the tank, or in terms of blending time or some readily evaluated solids-suspension criterion. If the application is relatively simple, a complete and detailed examination of the complicated fluid mechanics in a mixing tank is not usually necessary. If the process is complex then a full analysis of fluid shear rates and stresses, two-phase mass transfer, turbulence, and micro-scale shear rate and blending may be required.

It is sometimes possible to express a complex mixing process in terms of only one, or a few, simple velocity and pumping capacity relationships. Design in such a case is therefore straightforward and simple. Problems, however, can arise in distinguishing processes to which comparatively simple physical and visual concepts can be applied and those for which more elaborate qualitative and quantitative aspects are required to be considered.

3.4.3 Mixing of Powders, Pastes and Batters

The mixing of dry powders is normally carried out as a batch process in either vertical or horizontal mixers. Vertical mixers have a movable bowl in which the contents are mixed by mechanical agitation. Paddle agitators are commonly used and the shape of the impeller frequently conforms to the vessel walls. Planetary motion devices are commonly used in vertical mixers in which the agitator revolves in circle in addition to rotating on its own axis. This ensures that the entire mixer volume receives beating action and that there are no dead spaces.

Horizontal mixers are widely used for doughs in which gluten development is desirable. The mixers have a jacketed U-shaped trough. Water flowing through the jacket enables heat removal.

Example:

A largely aqueous-based liquid food is mixed in batch vessel. Assuming a Power number of 5 (for Re>5000) determine the power input through the impeller if an impeller has a diameter of 70 cm and speed of 30 rpm. The density and viscosity of the liquid food is 1000 $kg.m^{-3}$ and 0.02 Pa.s, respectively.

Solution:

The Power number for an impeller is

$$N_P = \frac{P}{\rho N^3 D^5}$$

The power for mixing is therefore

$$P = N_P \rho N^3 D^5 = 5 \times 1000 \times \left(\frac{30}{60}\right)^3 \times 0.7^5 = 105W$$

The power is 105 W. As a check, the Reynolds number is

$$\mathrm{Re} = \frac{\rho N D^2}{\mu} = \frac{1000 \times \frac{30}{60} \times 0.7^2}{0.02} = 12250$$

A Power number of 5 is therefore valid for Re greater than 5000.

Example

Bubbles of CO_2 gas were found to rise in carbonated beverage of density 1030 $kg.m^{-3}$ and viscosity 1.0 mPa.s for which the following observations were made:

Time (s)	1.0	2.0	3.0	4.0
Velocity ($m.s^{-1}$)	0.0225	0.04	0.0625	0.3

Determine the diameter and age of the bubbles when they detach from the nucleation sites, and the rate at which CO_2 enters the rising bubbles ($m^3(CO_2).m^{-2}.s^{-1}$).

Solution

Assuming the bubbles to be spherical, the rate of transfer into the bubbles is assumed to be proportional to the area of the bubble. That is

$$\frac{d(\frac{4}{3}\pi r^3)}{dt} = f\,4\pi r^2$$

The rate of change of bubble radius is therefore equal to the rate at which CO_z enters the bubble:

$$\frac{dr}{dt} = f$$

From the formation of the bubble, the radius at any time can be found by integrating to give

$$r = f(t + t_o)$$

The terminal velocity of a bubble of gas rising is approximately given by Stokes' law

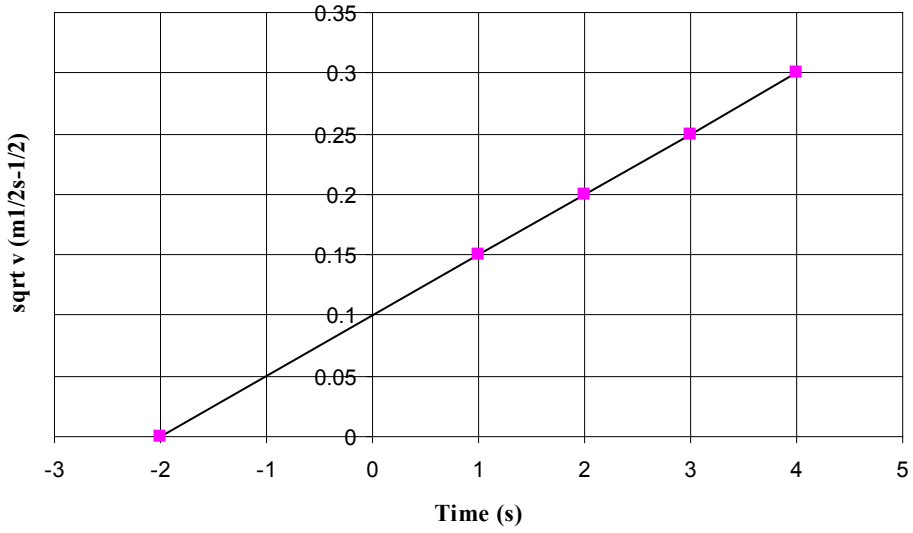
$$v = \frac{2\rho g r^2}{9\mu}$$

Then

$$\sqrt{v} = f\sqrt{\frac{2\rho g}{9\mu}}(t + t_o) = f\sqrt{\frac{2\times 1030\times 9.81}{9\times 0.001}}(t + t_o)$$

This is a straight line

Time (s)	1.0	2.0	3.0	4.0
√Velocity ($m^{1/2}.s^{-1/2}$)	0.15	0.2	0.25	0.3



The bubble therefore forms 2.0 seconds before detachment at which the terminal velocity is 0.01 ms^{-1}. This corresponds to a bubble radius of

$$r = \sqrt{\frac{9\mu v}{2\rho g}} = \sqrt{\frac{9\times 0.001\times 0.01}{2\times 1030\times 9.81}} = 6.7\times 10^{-5} m$$

That is, a diameter of 0.13 mm.

The rate of carbon dioxide transfer is therefore

$$f = \frac{r}{t + t_o} = \frac{6.7 \times 10^{-5}}{2} = 3.35 \times 10^{-5} m^3 (CO_2).m^2.s^{-1}$$

3.5 Novel Food Processing

In addition to conventional food processing, there are considerable demands on the food processing industry to develop new creative products in innovative ways. Some of the foods and processes do not conform to existing techniques and methods. A novel food is defined as a food which has not had an appreciable level of consumption or a process which has not previously been used. Such foods are required to be authorised according to the Novel Food Regulations legislation (EC) No 258197 of the European Parliament.

3.5.1 High Pressure Food Processing

The novelty and purpose of using high pressure instead of heat - as in conventional cooking - is to preserve and even improve food quality in terms of taste, flavour, texture and colour. Consumers nowadays generally expect the food that they buy to be of a high quality, minimally processed, 'natural', additive-free and high in nutritional value. The unique effects of pressure appear to be able to meet these requirements. Significantly, the covalent bonds of food components including saccharides, vitamins, lipids and pigments are able to resist the effects of high pressures in contrast to the highly damaging effects of heat. Pressure is generally only able to affect the weaker bonds and forces sufficient to alter the delicate molecular structures - as in the case of proteins.

High pressure food processing has been used in the destruction of micro-organisms, the activation and deactivation of enzymes, the change of functional properties such as foams, gels and emulsions, and the control of phase change such as fat solidification and ice melting point. The sterilisation properties of high pressure food processing have been compared to that of heat treatment. Like heat, micro-organisms differ significantly in their ability to withstand pressure. Bacteria, yeasts and moulds are readily killed by high pressure while bacterial spores and some viruses are particularly resistant; spores being only inactivated by pressure after germination. As an analogy to the heat treatment of pasteurisation, the pressure sterilisation is appropriately termed *pascalisation*.

Another difference between thermal and high pressure processing is that while heat is conducted through the exterior of foods to penetrate the interior, which takes time and often with over-cooking of the surface, pressure is applied instantaneously and uniformly. Also, unlike heat treated food, pressure processing is more dependent on the quality of the raw food material.

An interesting effect of high pressure is the depression of the freezing point of water. At 200 MPa, for example, the freezing point is reduced to -22°C. The problem with conventionally storing frozen food is that much of the textural quality is lost during the freezing or thawing often due to the damaging effects of ice crystals. A possible application of high pressure may be to cool food below its freezing point at high pressure and then by releasing the pressure instantly freeze the food. Tests have shown that the rapid and uniform freezing effect has been found to preserve better food texture on thawing.

The cost of pressure-processed food is currently higher than that of heat processed food even though pressure processing actually consumes less energy. The cost of reaching a pressure of 400 MPa is about the same as heating from only 20°C to 25°C. The reason for the high cost is because the equipment needed is very expensive and makes up about 80% of the total production costs. In spite of the high cost of the equipment, the sales of high pressure processes foods continue to rise despite retail prices being typically twice those of conventionally processed products. At the moment the improved quality to be gained by pressure processing has found a niche market among certain consumers who are willing to pay a premium. The future may well lead to pressure processed foods eventually being more commercially competitive and affordable to all.

The processing of foods by high pressure offers the creation of many entirely new and exciting food textures. Pressurised beef muscle has a texture like raw ham but without a change in taste. Fish and pork muscle become more glossy, transparent, dense, smooth and soft. Fruit-based jams, jellies, purées and juices have exceptional 'just squeezed' flavour and striking natural colour. Protein from soya, milk and eggs can form soft gels that can be used to make new types of desserts and yoghurts. The foaming and emulsifying properties of egg white albumins can also be influenced by pressure by careful control of the molecular unfolding.

The way in which food is pressurised is similar to the way food is heated. Solid-type foods are first sealed into plastic bags and then loaded in a thick-walled steel pressure vessel. Once loaded with food packages and closed, the vessel is filled with a liquid such as water mixed with a small amount of soluble oil for lubrication and anti-corrosion purposes. Liquid foods, on the other hand, are placed directly into the vessel. The thickness of the vessel wall is determined by the operating pressure, volume and the expected number of times the vessel is to be used.

After removing any remaining air from the vessel, the vessel is pressurised by a powerful piston. A variety of jams, fruit yoghurts, fruit jellies, salad dressings and fruit sauces are now already being processed by high pressure. Citrus juices can typically be made at a rate of up to 6000 litres per hour.

While the many technical problems that have previously hampered high-pressure research and development have now been overcome, there is still much of the fundamental science of high pressure to be understood, particularly at the molecular level.

4 Food Safety

4.1 Introduction

Food safety has become one of the biggest consumer issues of recent years. From the public perception that food additives are harmful, to the high profile scares about Listeria, Salmonella and BSE (mad cow disease), there has been an increasing public feeling of distrust of the mass-market food industry. This is despite the fact that modern processing methods can now deliver a range of high quality foods at unprecedented levels of production. Nevertheless, these same production methods bring with them a responsibility to ensure that the processed foods can be stored and used safely in the home. Yet despite public concerns about issues such as genetic modified foods, pesticides, fertilisers and animal feeds, one of the biggest threats to food safety remains food poisoning bacteria.

The challenge for the food industry is to use methods of preparation and processing that destroy pathogens and prevent recontamination of food. Given the variety of food poisoning organisms and how they can thrive, this is by no means a small challenge.

There are several bacteria that pose a significant threat to food safety. Most can be killed by cooking and re-infection can be avoided by preventing cross contamination and by appropriate cold storage. The bacterium *Bacillus cereus* is found on virtually every agricultural commodity, but generally at levels too low to cause illness. Eating foods on which the organism has grown and formed toxins, however, will result in food poisoning. Toxins are responsible for illness, causing diarrhoea and vomiting. These can be very resistant to heat and extremes in pH. In mild cases, full recovery may be within 24 hours.

Only in the past decade or so has *Campylobacter* bacteria been recognised as the cause of enteritis. Many cases of infection have been associated with unchlorinated water and unpasteurised milk, but it is also often found raw poultry meat. The bacterium infects the intestinal tract, excreting toxins causing abdominal pain, fever, and diarrhoea and vomiting. The illness usually up to a week to materialise and full recovery can take a further week.

Occurring on almost all foods, the toxin produced by *Clostridium botulinum* bacterium is among the most toxic of all naturally occurring substances. The lethal dose may be as little as 0005mg. Fortunately, it is inactivated by heating at 90°C for just a few seconds. Symptoms of infection include weakness and fatigue followed by blurred vision and difficulty in swallowing. Death is usually the result of respiratory failure.

Through careful control, incidents of poisoning by *C. botulinum* from commercially processed foods are rare. Cooking a food container to ensure that its slowest heating point is exposed to temperatures equivalent to 121°C for three minutes (known as a Botulinum Cook) is generally sufficient to kill the organism.

Listeria monocytogenes can survive well for several weeks at -18°C in various foods. However, it does not normally survive commercial pasteurisation. Most *L. monocytogenes* cases occur in people predisposed to the infection such as those with illness. Not all strains of *L. monocytogenes* are pathogenic but those that are, are haemolyphic in that they destroy red blood cells. Infection usually occurs via the intestine.

There are over two thousand identifiable strains of Salmonella. The two strains of concern in Europe are *S. enteritidis* and *S. typhimurium*. Salmonellae invade the small, and sometimes the large intestine, where they may overcome body defences to reach the bloodstream and give rise to abscesses on various tissues. Invasive strains pass into the lymphatic system and are engulfed by phagocytes. These bacteria re-enter the bloodstream causing septicaemia. Since low numbers of salmonellae can cause illness it is important to ensure their absence from ready-to-eat foods. Salmonellae are also often associated with raw eggs and poultry products.

Staphylacoccus aureus occurs widely on the skin and mucous membranes of warm-blooded animals, including humans. Food can be contaminated through poor hygiene and storage, allowing food poisoning enterotoxins to form. *S aureus* cells are easily destroyed by heat, but the toxin is heat resistant and will survive some sterilisation processes. Symptoms of enterotoxins include nausea, abdominal cramps and diarrhoea. In severe cases headache and collapse may occur. Recovery is usually rapid.

There are ten species of *Vibrio* which have food-borne pathogenic potential. Found in seafood, the bacteria prefers to grow in the presence of salt and is easily destroyed by drying. Food poisoning is thought to be associated with the production of a heat resistant haemolysin causing the destruction of red blood cells. The symptoms are therefore similar to those for salmonellosis.

There four types of pathogenic *Escherichia coli* bacteria that have been associated with food-borne disease. The most notorious of these is *E. coli* 0157. Though often associated with undercooked meat, *E. coli* 0157 has been found on many uncooked foods, and has caused many food poisoning cases during the past decade, some of which have been fatal.

4.2 HACCP

The emphasis on food safety within the industry around the globe is based on the principles of prevention rather than cure. There has been universal adoption of the Hazard Analysis Critical Control Point (HACCP) principles for identifying hazards and putting in control procedures to minimise risk. Testing is now seen as a means of verifying the HACCP system, rather than checking on the safety of food.

Originally developed by NASA for the prevention of contamination in space, HACCP was designed to be a system and set of procedures for prevention. Applied to the food industry, it means that all elements of contamination risk in a food operation are checked thoroughly and is a systematic method of assessing and minimising or, if possible, eradicating risk.

The globalisation of the food industry means that foods may be comprised of components which are harvested, processed and shipped from many countries. Improper storage or handling at any point or place can result in the overall food being contaminated from unidentifiable sources. Under HACCP the food processor is required to develop and follow a HACCP plan that identifies the possible hazards, the steps at which controls must be applied to prevent the hazards from occurring, the safety limits that apply to the control point, and the monitoring and record-keeping necessary to document and verify that the control has been applied.

An example of a control point is a cooking step in which the food must be subjected to temperatures sufficient to kill any harmful organisms. The HACCP plan would include the temperature that the cooking must attain, and also the means of monitoring that temperature, the type of record used for documenting the reading; the corrective action steps to take if the required cooking temperature is not met; and procedures for verifying that the plan is being properly implemented.

A likely source of microbial hazards to be controlled under HACCP is cross-contamination. Personal hygiene of food handlers is the main source of cross-contamination, but pests such as rodents, birds, flies and cockroaches can also cross-contaminate food during processing. Sanitation programmes must include pest controls to prevent live, mobile pests from cross-contaminating food during processing and storage. These controls are the basis for good manufacturing practices.

Under HACCP, these sanitation programmes are called prerequisite programmes because they provide the foundation for the HACCP controls and must be properly applied if the HACCP controls are to be effective. They should not introduce additional hazards. The challenge is therefore to identify all hazards and develop and implement a HACCP plan that is able to control all food safety hazards.

HACCP applies to every food handling site and also includes cafés, restaurants, bakeries and other food handling sites, including abattoirs. Whatever the operation, there must be a practical system in operation, ensuring that the highest standards of hygiene and food safety are maintained for the benefit of the public. If a site, company or organisation does not have an HACCP procedure, severe penalties can be imposed including fines, closure, and recall of all foods sold to the public. A breach of major severity may lead to a custodial prison sentence.

The HACCP consists of seven distinct steps:

1. Assess the hazards
2. Identify critical control points
3. Set up control procedures and standards for critical control points
4. Monitor the critical control points
5. Take any corrective actions
6. Establish effective record keeping
7. Verify that the system is working

For food handling sites HACCP monitors the minimum number of critical points necessary to ensure a safe product. Decisions about the existence of critical points are based on scientific facts and statistics. A well-run HACCP system can control each critical point to eliminate occurrence of hazards.

4.3 Hygienic Design

The design of process equipment and plant should ensure that the food being processed can be processed safely without the risk of contamination either through expose to contaminated air, liquids or surfaces. Contamination may also be due to food process operators. Equipment should therefore be manufactured from approved food-grade materials and be designed such that the equipment can either be disassembled and cleaned manually or cleaned automatically in place. There should be no dead spots and cleaning programmes designed to remove chemically and physically any material which may have adhered to the surface. The cleaning agents should also be thoroughly washed from the equipment after cleaning.

From raw ingredients to the finished product, a food processing facility may have areas consisting of warehousing, dispatch, raw ingredient storage, cold storage, chillers, ingredient mixing, production, packaging, utensil and equipment wash, laboratories, plant rooms, mezzanine decks, staff changing rooms, toilets and offices. Each area has its own particular requirements for design.

It is essential that floor finishes satisfy all legislation. In high-risk zones the floor finish is required to be seamless, hygienic, durable and easy-to-clean and maintain. The flooring must also be able to withstand all, or a combination of chemical resistance, thermal shock, impact, abrasion resistance, flexibility on mezzanine decks. All facilities require a floor finish to be slip-resistant, hygienic and easy to maintain. Floor materials should be able to withstand aggressive and abrasive cleaning as well as steam cleaning processes that are essential for maintaining hygiene. The floor is likely to have to impact resistance and well as resistance to chemical attack and high temperatures. Careful planning is needed in the replacement or refurbishment of existing floors, to make maximum use of downtime, to keep lost production to a minimum and to avoid any risk of odour contamination.

Although there is a wide variety of flooring materials available only a few are suitable for the food industry. Seamless resin compounds and slip-resistant heavy duty vinyl flooring materials are the most popular for high risk zones and can satisfy most or all of the requirements of food manufacture and retail. Resin flooring systems range from high solid content coatings for low-traffic areas to heavy-duty screeds for high-risk zones, such as ingredient mixing and blending, production, warehousing, freezers and chillers. There are many resin systems available, including acrylics, polymers, polyesters, epoxy and polyurethane. Modern resin systems such as polyurethane screeds are at the forefront of resin development and constructed for the harsh environment of food processing and manufacturing offering excellent chemical resistance. In less demanding low-risk areas of laboratories, staff changing rooms and toilets, epoxy resin systems or slip-resistant vinyl materials offer a wide range of finishes, thickness and a firm grip underfoot.

Good housekeeping and maintaining general tidiness is essential to ensure risks are reduced to a minimum and the avoidance of contamination. This can be improved by installing trays for the collection of waste. Sweeping, shovelling or vacuuming of spilt material rather than hosing it down the drain should be used. Procedures for manual cleaning processes should also ensure that hoses and water lances use trigger controls to minimise the amount of wash down water. High pressure, low volume water systems are preferable.

In using cleaning chemicals, operators should be trained in the handling, making up of working solutions and their application. The concentration of the chemical agent should not be too high and the overuse of chemicals avoided, particularly where manual dosing is used.

In the design of Cleaning-in-Place (CIP) systems, remnants of dry product should be expelled or removed before the start of the wash cycle by gravity draining, pigging or air blowdown. A pre-rinse is then used to enable remaining product to be recovered for re-use or disposal. Turbidity detectors can be used to maximise product recovery.

A CIP programme should be optimised for the plant or vessel size and soiling type to ensure that the automatic dosing of chemicals are set at the correct concentrations (see Table 4.1). The programme should include internal recycling of water and chemicals, a recycle control on conductivity rather than time with a continuous cleaning of re-circulated solutions.

Processing equipment and production facilities are cleaned and sanitised periodically, with the frequency varying according to products and processes. The aim of cleaning and sanitation is to remove product remnants from the foregoing process and remove other contaminants and microbes.

Manual cleaning means that the equipment to be cleaned is taken apart and manually cleaned (brushed) in a cleaning solution. Only mild conditions, with regard to temperature and cleaning agents, can be used.

Cleaning in place (CIP) is used especially for closed process equipment and tanks. The cleaning solution is pumped through the equipment and is sometimes distributed by sprayers. The cleaning programme is mostly run automatically and includes a pre-rinse with water, circulation with a cleaning solution, and intermediate rinse, disinfection and a final rinse with water. In automatic CIP systems the final rinse water is often reused for pre-rinsing. Typical cleaning temperatures are around 90°C and used together with strong cleaning agents.

In high-pressure jet-cleaning, water is sprayed at the surface to be cleaned at a pressure of about 40 to 65 bar. Cleaning agents are injected in the water and temperatures up to 60°C are used. An important aspect of the cleaning action is due to the mechanical effect of cleaning. There are, however, hygiene implications of over-splash and aerosols.

In foam cleaning, a foaming cleaning solution is sprayed on the surface to be cleaned. The foam adheres to the surface and remains on the surface before being rinsed away. High-pressure jet-cleaning and foam cleaning is generally applied for open equipment, walls and floors.

Cleaning agents used in food and drink industry include alkalis such as sodium and potassium hydroxide, sodium carbonate, acids such as nitric acid, phosphoric acid, citric acid and gluconic acid. Formulated cleaning agents containing chelating agents include EDTA, NTA, phosphates, polyphosphates, phosphonates as well as and surface active agents.

Table 4.1 Cleaning-in-Place

Component	*Solubility*	*Removal*	*Difficulties*
Sugars	Water soluble	Easy	Caramelisation
Fats	Fat soluble	Difficult	Polymerisation
Proteins	Water insoluble	Very difficult	Denaturation
	Alkali soluble	Very difficult	Denaturation
Sugar & Protein	Alkali soluble	Very difficult	Denaturation
Mineral salts	Water soluble	Varies	Use hot water
	Acidity dependent	Varies	High temperature

4.4 Food Packaging

The function of food packaging is to provide protection from physical damage, chemical attack, environmental contamination and tampering and as well as forming good product utilisation. Food packaging is designed for each food product in order to make it easier or more convenient for a consumer to use. The packaging is also designed to provide good communication to the consumer or user. In particular, packaging should convey details of the product identity, the mount and number of servings, ingredient contents, nutritional content, preparation instructions, consumer service information and include coupons, recipes and any promotional offers.

Food packaging is required to be non-toxic, sanitary, durable, easy to use, economical, recyclable, designed to extend product shelf-life and provide a good barrier. Packaging may therefore be designed to be permeable, semi-permeable, or impermeable to water as a liquid or vapour, oxygen, carbon dioxide, volatiles and light. After use, packaging can be re-used, recycled, sent to landfill or incinerated.

4.4.1 Glass

Glass is fabricated from sand, soda ash, and limestone. Colorants and coatings may be added. Glass has the advantage of being inert, good optical qualities, easily recycled although is fragile, heavy and requires a lot of energy for its production.

4.4.2 Metal (Steel Cans)

Fabricated from steel with a thin tin and/or polymer coating, coatings protect the steel and prevent electrochemical reactions (corrosion) between the container and the food. The advantage is that it is hermetically sealed, offers an impermeable barrier, has good heat transfer properties, is strong, can be made on site. However, it may react with food and unfilled cans dent easily and are heavy.

4.4.3 Metal (Aluminium Cans)

Aluminium cans are lightweight, resistant to corrosion, easily formed and recyclable. They are, however, fragile and must be pressurised up to 6 bar to offer appreciable strength.

4.4.4 Plastic

Plastic can be moulded and drawn into flexible films and used either with or without coatings. The advantage of plastic is that it lightweight and can easily be formed into shapes. It is, however, difficult to achieve desired barrier properties for some products particularly against gas diffusion.

4.4.5 Paper

A variety of strengths are available with or without coatings. Paper is not a good barrier and loses strength in high humidity environments.

4.4.6 Paperboard

This is made from carton stock with or without coatings. It can be heat stable and may be used for cooking in both conventional and microwave ovens.

4.4.7 Corrugated Cardboard

This is used to make shipping containers and is made from several layers of paper with internal flutes that provide strength to the material. The paper can be from a variety of grades, is inexpensive and easily recycled.

4.4.8 Composite packages

These comprise three layers with the outer layer being composed of polyester film that provides thermal resistance, strength, and printability, a layer of aluminium foil to provide barrier properties and an inner layer of polypropylene to provide heat seal integrity. They are lightweight, easy to open but expensive and not recyclable.

4.4.9 Food Labelling

Food labelling must comply with the EU food labelling requirements. Food labels provide information from the manufacturer to the consumer. They allow the consumer to know exactly what they are buying. They also provide instructions for storage and preparation, and allow the consumer to make dietary choices as well as judgement on value for money.

By law, most food products must include the following information, though some products may be exempt from one or more of these conditions.

Product name
Ingredients list (in descending order of weight)
Shelf-life (use-by or best-before date)
Storage instructions
Name and address of either the manufacturer, packer or EC seller
Country of origin
Weight (or volume)
Instructions for use

Although not a legal requirement, other labelling can also include:

Instructions for long term storage
Instructions for opening
Serving suggestions
Consumer advice details
Promotional details
By appointment
Logos and pictures
Recipes
Bar codes

Example:

The following label is taken from a pot of cottage cheese:

NUTRITION INFORMATION		
TYPICAL VALUES	PER 100g	PER POT
Energy	405kJ 96kcal	809kJ 192kcal
Protein	9.9g	19.8g
Carbohydrate	6.5g	13.0g
of which sugars	5.1g	10.2g
Fat	3.4g	6.8g
of which saturates	2.0g	4.0g
Fibre	1.0g	2.0g
Sodium	0.3g	0.6g

Confirm that the energy requirement is 809 kJ.

Solution:

In calculating the energy value on the label the following conversion factors are used:

1 g carbohydrate = 17 kJ (4 kcal)
1 g protein = 17 kJ (4kcal)
1 g fat = 37 kJ (9 kcal)
1 g ethanol = 29 kJ (7 kcal)
1 g organic acid = 13 kJ (3 kcal)

In this case:

Protein:	19.8 g x 17 $kJ.g^{-1}$	= 336.6 kJ
Carbohydrate:	13 g x 17 $kJ.g^{-1}$	= 221 kJ
Fat:	6.8 g x 37 $kJ.g^{-1}$	= 251.6 kJ
	Total	= 809.2 kJ

5 Thermal Processing

5.1 Introduction

The purpose of thermal processing foods is to destroy pathogenic and spoilage micro-organisms and their spores as well as to inactivate enzymes and metabolic reactions resulting in senescence. However, high temperatures can also degrade product appearance, texture, and nutrient quality. The advantages of thermal processing in terms of food safety and increased shelf life must be balanced with the disadvantages of loss of nutrient and sensory attributes.

A number of thermal processing methods are commercially used each using a different temperature and treatment time strategy:

Blanching:
This is a mild heat treatment, usually applied to fruits and vegetables to denature enzymes and is often used before freezing. It uses either hot water above 80°C or live steam.

Pasteurisation:
Pasteurisation destroys pathogenic micro-organisms and extends the shelf life of a food. Pasteurised products may still contain many viable organisms capable of growing and causing spoilage defects. An example is milk in which pasteurisation is usually combined with another means of preservation such as refrigeration. The levels of pasteurisation used to thermally process milk are:

- Low Temperature Long Time (LTLT): 63°C for 30 minutes
- High Temperature Short Time (HTST): 72°C for 15 seconds
- Ultra High Temperature (UHT): 135°C (or above) for 2 seconds

Commercial Sterilisation:
Commercial sterilisation refers to the destruction of all pathogenic and toxin-forming organisms, as well as other types of organisms which, if present, could result in food spoilage under normal handling and storage conditions. These foods may contain a small number of heat resistant bacterial spores, but under normal handling and storage conditions will not multiply. Types of commercially sterile processes include canning, bottling, and aseptic processing. Most commercially sterile food products have a shelf life exceeding two years.

Sterilisation
Sterilisation refers to the complete destruction of all micro-organisms, including both vegetative cells and spores.

Called the logarithmic order of death, bacteria are destroyed by heat at a rate that is proportional to the number present in the food being heated. Expressed as the "D-value," or decimal reduction time this is the time in minutes at a specific temperature required to destroy 90% (or one log cycle) of the organisms in a population. The time (or number of D-values) required depends on the processing temperature, type of micro-organism(s) that are in the food and the physical and chemical characteristics of the food product.

Example:

Consider a food containing 1,000,000 viable, pathogenic micro-organisms. The D-value for killing this pathogen is one minute at 121°C. Determine the time taken to reduce the population to 1 viable cell.

Solution:

The reduction of pathogenic micro-organisms in a food that is thermally processed at 121°C is given by

Cell count	Elapsed time at 121°C
1,000,000 to 100,000	1 min
100,000 to 10,000	1 min
10,000 to 1,000	1 min
1,000 to 100	1 min
100 to 10	1 min
10 to 1	1 min
Total elapsed time	= 6 mins

This is referred to as a "6D process," in which only 1 in 1 million bacteria survive the thermal processing. In a 12D process 1 in 1 million million cells survive. This is commonly used in commercial canning.

The important factors for assuring adequate thermal processing include size and shape of the can, ingredients and pH of the food product and viscosity of the food product. The mechanisms of heat transfer are radiation, conduction and convection. In radiation, infrared energy is absorbed by food surface while conduction is the transfer of heat through the solid body and convection is through convection currents in liquids and gases.

Not all packaging materials conduct heat at the same rate. The cold point in a can or food mass is the location that is last to reach the final heating temperature. A thermocouple can be used to determine location of the cold point. Higher temperatures facilitate shorter processing times for microbial destruction, and shorter time favours retention of desirable quality attributes.

5.2 Thermal Death

As with all living things, micro-organisms are sensitive to heat. To destroy a micro-organism requires thermal energy that must be sufficient to be lethal. This energy must be held for a sufficient period of time to ensure death. For each type of micro-organism it is necessary to identify the temperature and exposure time that is required.

Temperature is a measure of the vibrational energy of molecules. There is a certain probability that the organism will die after a given time above some threshold temperature. The cause of thermal death is thought to be due to the irreversible denaturation of certain enzymes critical for DNA or RNA replication.

Empirical observations have shown that at constant temperature, many micro-organisms will die at a rate that is first order with respect to time. The time rate of change of organisms that have survived the heat treatment, can be described mathematically as

$$\frac{dN}{dt} = -kN$$

By considering isothermal conditions the assumption that k is a constant is valid. The equation holds true for a wide range of organisms even when more than one species of organism may be present. The number of surviving micro-organisms is therefore found from

$$\int_{N(t_o)}^{N(t)} \frac{dN}{N} = -k \int_{o} dt$$

Integrating and rearranging

$$N(t) = N(t_o)e^{-k(t-t_o)}$$

where $N(t_o)$ is the number of organisms initially present at time t_o. Note that the number of remaining viable organisms will approach zero only as the treatment time approaches infinity. In other words, sterility can not be achieved according to this model. The model is, however, widely used. This is because the model is based on probability. This is due to the fact that this is a mathematically continuous model used to describe the behaviour of a collection of discrete organisms, each of which will react to the application of heat in a slightly different way.

The time required to reduce the population of a particular contaminating micro-organism by a factor of ten is a commonly mentioned quantity and is calculated as

$$t = \frac{-1}{k \ln\left(\frac{N(t)}{N(t_o)}\right)} = \frac{-1}{k \ln 0.1}$$

The Decimal Reduction Time is the time taken at constant temperature for a ten-fold reduction in surviving micro-organisms. For a food to be sterile will require a number of log cycles. A 12 cycle reduction or 12D cook is required for canned processes. This is called the thermal death time, t_D, and is a term used with thermal processing of foods and is defined as the time required for the complete kill of all organisms in a given suspension. Experimentally, measurements can be made of the number of organisms surviving a particular treatment and then extrapolating to zero. Practically, a commonly used approach to estimate the thermal death time is to determine the thermal death constant, and calculate the time required to reduce the viable count to one organism.

Defining the initial concentration of organisms as 10^B, then

$$\ln\left(\frac{N_{(t)}}{N_{(t_o)}}\right) = \ln\left(\frac{1}{10^B}\right) = kt_D$$

Note that where there is a significant time for heating and cooling of the solution, the heating time and the cooling time also contributes to the killing of organisms, as well as to the denaturation of other heat sensitive materials. It is therefore necessary to integrate the kinetic death model from the time at which the lethal temperature is first reached until the time when the solution is cooled below this temperature.

A widely used term is the F_{121} value. This the thermal death time at 121°C. Another term is the Z parameter which is the temperature rise required to bring about a ten-fold decrease in the thermal death time (see Table 5.1).

Table 5.1 F121 and Z Parameters for Bacteria, Vitamin B1 and Chlorophyll

	Z (°C)	*F (min)*	*E(kJ.mol⁻¹)*	*Temp (°C)*
Clostridium botulinum	5.5-10.0	1.2-3.6	265-340	104+
Bacillus stereothermophilus	7.0-12.0	4.0-5.0	230-400	110+
Vitamin B_1 (Thiamin)	25-27	120-247	90-125	109-149
Folic acid	37	28,000	46	100+
Non-enzymatic browning	17-39	4.8-480	100-250	100+
Peroxidase	26-37	24-36	67-85	100+
Chlorophyll (green leaf)	45-79	13-48	30-90	100-149
Betamin (beetroot)	59	570	46	100+

It is possible to relate thermal death time, t_D, to the F_{121} and Z parameters for which the gradient is

$$\frac{\log_{10} 10F_{121} - \log_{10} F_{121}}{Z} = -\frac{1}{Z}$$

The gradient is also given by

$$\frac{\log_{10} t_D - \log_{10} F_{121}}{121 - T} = -\frac{1}{Z}$$

Rearranging

$$\log_{10}\left(\frac{t_D}{F_{121}}\right) = \frac{121 - T}{Z}$$

or

$$t_D = F_{121} 10^{\frac{121-T}{Z}}$$

The fraction of surviving spores reaching thermal death dS in time dt is therefore

$$dS = \frac{1}{t_D} dt$$

Since the total fraction is unity

$$\int dS = 1.0$$

then

$$\int \frac{10^{\frac{T-121}{Z}}}{F_{121}} = 1.0$$

The integral can be evaluated graphically or by numerical integration.

Example:

The thermal death times of spores of a contaminating micro-organism in a food product are 6 minutes at 120°C and 2 minutes at 125°C. Determine the Z and F_{121} parameters of the product. The food is canned and sterilised in an autoclave with steam at 1.0 barg. Temperature-time data for a test can was obtained as follows:

Time (min)	Temperature (°C)
85	102
90	104
95	106
100	108
105	110
110	111
115	112.5
120	113.5
125	114.5
130	100
135	95

Using the Z and F_{121} values, determine whether the food product is sterilised.

Solution:

The Z and F_{121} parameters are related by

$$\log_{10}\left(\frac{t_D}{F_{121}}\right)=\frac{121-T}{Z}$$

where t_D is 6 mins when T is 120°C and t_D is 2 mins when T is 125°C. Thus

$$Z=\frac{5}{\log_{10}3}=\frac{5}{0.477}=10.5^{o}C$$

and

$$\log_{10}\left(\frac{2}{F_{121}}\right)=\frac{-4}{10.5}$$

Thus

$$F_{121}=5\,\text{min}$$

Using the Z and F_{121} parameters it is necessary to determine t_D and its reciprocal (sterilisation rate). The time interval, Δt, is 5 minutes.

Time (min)	Temperature (°C)	t_D (min)	$1/t_D$ (min^{-1})	$1/t_D\Delta t$
85	102	320	0.0031	0.0155
90	104	206	0.0048	0.0240
95	106	132	0.0076	0.0380
100	108	86	0.0116	0.0580
105	110	55	0.0182	0.0910
110	111	44	0.0227	0.1135
115	112.5	32	0.0314	0.1570
120	113.5	25	0.0400	0.2000
125	114.5	20	0.0500	0.2500
130	100	500	0.0020	0.0100
135	95	1500	0.0001	0.0005
			Total	0.9575

A plot of *1/tD* versus time results in an area under the graph corresponding to a value less than 1.0 concluding that the food is just short of being sterilised.

Example:

The food product is canned and sterilised in an autoclave. The heating rate is constant at 1°C per minute. If the Z and F_{121} values are 9.19°C and 5.45 minutes, respectively, determine the time to sterilise the food product and the final temperature of the food if the starting temperature is 20°C. Ignore any cooling that would subsequently be used.

Solution:

A iterative approach can be taken to satisfy the criteria that

$$\int_0 \frac{10^{\frac{T-121}{Z}}}{F_{121}} dt = 1.0$$

Using increments of 1 minute (and therefore 1°C), the criteria is satisfied after 102 minutes, corresponding to a temperature of 122°C.

Alternatively, the ramped temperature increase can be substituted where

$$T = 20 + bt$$

So the integral becomes

$$\int_0 \frac{10^{\frac{bt-101}{Z}}}{F_{121}} dt = 1.0$$

Integrating

$$\frac{10^{\frac{-101}{Z}}}{F_{121}} \left[\frac{10^{\frac{bt}{Z}}}{\frac{b}{Z}\ln 10} \right]_0^t = 1.0$$

gives

$$t = \frac{Z}{b}\log_{10}\left(\frac{F_{121}\frac{b}{Z}\ln 10}{10^{\frac{-101}{Z}}} \right) = \frac{9.19}{1}\log_{10}\left(\frac{5.45 \times \frac{1}{9.19}\ln 10}{10^{\frac{-101}{9.19}}} \right) = 102\,\text{min}$$

As above, the final temperature is therefore

$$T = 20 + bt = 20 + 1 \times 102 = 122^{o}C$$

5.3 Canning

Canning is used as a long term storage method for many food products. When meat, fish or fruit products are hermetically sealed in a container, any accompanying micro-organisms, if not otherwise destroyed, will multiply if conditions are favourable. Microbial destruction is therefore the core to the process of canning. High temperatures are required the completely destroy bacterial spores although high temperatures may also influence the organoleptic properties of the contents of the cans. It is therefore necessary to determine the time and temperature required to sterilise the food and still produce a desirable product.

In the canning of meat, meat is delivered to the canning factory in the form of carcasses, quarters, or smaller pieces. After it has been checked for quality, it is freed from bone, tendons and fat, sorted, trimmed and then cut into small pieces which helps filling. The meat is partially cooked meat is filled into cans. More meat is overfilled to compensate for moisture loss during sterilisation. Meat jelly is prepared and added which acts as a binder and improves the appearance and palatability of the canned meat. A lid is then placed and sealed, and the cans then placed in a steam autoclave to be heated for a specified time.

5.4 Milk Processing

The dairy industry which has been established on practical experience over centuries is today a highly complex organisation responsible for producing and distributing processed milk and its associated products. Production of milk begins on the farm. The milk that is of interest comes from cows, goats and, to a certain extent, sheep. Breeds and characteristics of dairy animals influence the milk quality. From the farms, the milk is sent to milk processing plants where it is subdivided into heat-treated milks (pasteurised or sterilised) and homogenised, soft curd, irradiated and fermented milks. The treatment of milk is focussed on the destruction of the Mycobacterium tuberculosis bacilli that is responsible for causing tuberculosis, which is a disease of the lungs.

The composition of milk varies with the age and breed of animal, the way the animal is fed and the elapsed calving time. Raw milk is blended so as to annul any variations. When milk is heated extra care is taken to ensure that milk composition remains unaltered.

Named after the 19th centaury scientist Louis Pasteur who first discovered that spoilage organisms in wine could be inactivated by applying heat at temperatures below its boiling point, the pasteurisation of milk depends on the total count of heat resisting organisms present. To produce a pasteurised product of satisfactory quality, it is essential that the raw milk supply is also of good hygienic quality. Pasteurisation methods are usually standardized and controlled by national food safety agencies. In the UK, a temperature of not less than 71.7°C for at least 15 seconds is used (see Figure 5.1)

The conditions of pasteurisation are similar worldwide albeit with minor variations in time–temperature combinations, cooling temperatures and testing procedures. The pasteurisation process, which is a mild form of heat treatment in which the milk has no appreciably cooked flavour and a low whey protein denaturation of between 5% and 15%, is either carried out as a batch or continuous process.

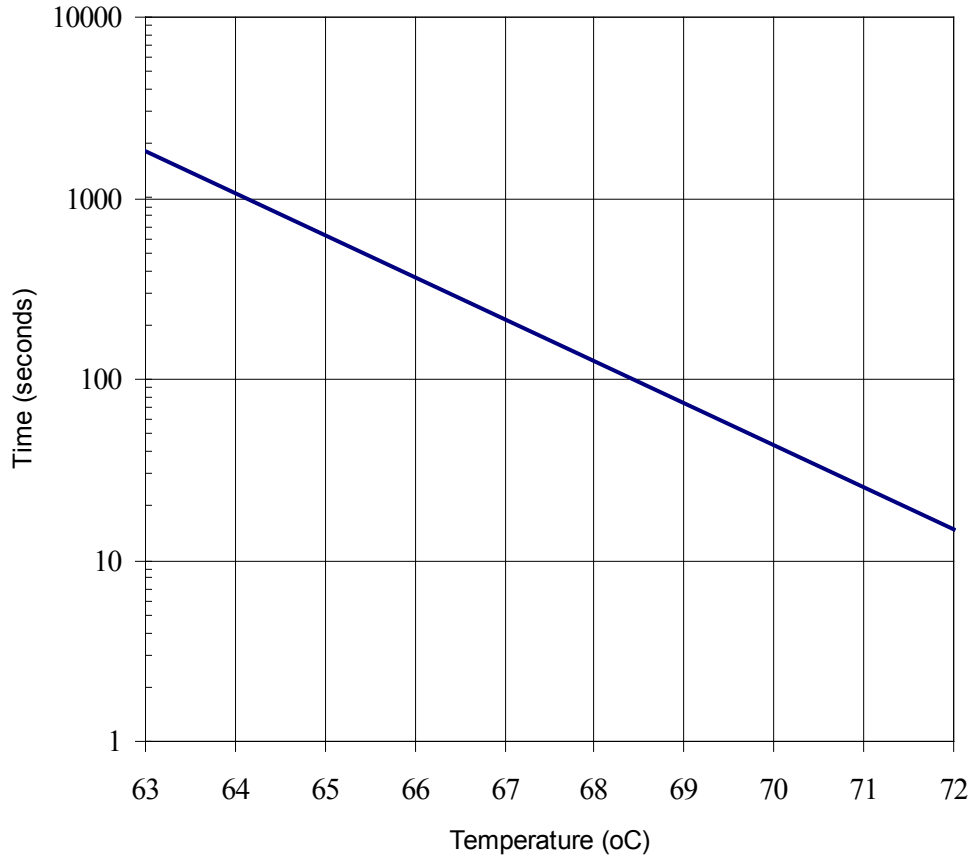


Figure 5.1 UK Pasteurisation Standards

5.4.1 Holder Process

The Holder thermal process requires a temperature of not less 62.8°C not more than 65.6°C for at least 30 minutes, and then immediately cooled to a temperature of not more than 10°C. Regarded as being uneconomic on the large scale, it is used as a batch process for pasteurisation of human breast milk for neonatal purposes due to its low temperature preserving essential growth hormonal components.

5.4.2 High Temperature Short Time HTST

In the HTST process, raw milk at 10°C enters the process through the regeneration section. Raw milk and is heated to 68.6oC by hot milk, which, in turn, cools. The now warm milk enters the final heating section where hot water or electricity is used to heat it to the desired temperature. It then passes through a holding tube and through the regeneration section, and enters the main water and chilled water-cooling sections.

Most HTST pasteurisers use plate heat exchangers, which offer a large surface area for heat transfer within a compact space. The gap between the plates is narrow so as to induce turbulence and to maintain the required pressure drop in the system. Such heat exchangers are suitable for low viscosity fluids, which are sensitive to heat.

5.4.3 Homogenisation

Homogenised milk is produced from raw milk that is first warmed and then forced through a fine aperture. This breaks down fat globules into smaller particles that remain distributed through the milk. The milk is then either pasteurised by bottling, sealing and heat treating at 110°C to 115°C for 20 to 30 minutes and allowing it to cool, or it is UHT processed.

5.4.4 Ultra High Temperature UHT

Invented in the 1960s, UHT is used to kill spores found in milk but is also used for processing fruit other liquid diary products, fruit juices and soups. UHT processing involves short times of one to two seconds at temperatures exceeding 135°C. Continuous UHT process equipment is similar to that used in the HTST pasteurisation process and uses plate heat or tubular heat exchangers.

The of shelf life UHT processed milks is typically nine months. However, due to the high temperatures used in UHT processing, Maillard browning can occur resulting in a change in taste and darkening of colour.

6 Preservation by Refrigeration

6.1 Introduction

All living things age with time. For fruit and vegetables, ageing can be extended beyond harvesting. The process of ripening can be slowed by cold storage. However, a carefully controlled temperature must be maintained that is sufficient to slow down the ripening processes and the activities of bacteria and fungi yet sufficient to prevent it from failing to ripen, ripen too quickly and go rotten, or be very prone to attack by fungi. Grapefruit, oranges and tomatoes, for example, are required to be stored at 7°C while bananas require a higher temperature of between 12°C and 14°C and. Apples range from -1°C to 4°C.

The fact that the activity of bacteria is reduced at low temperatures is of great importance in extending the shelf life of foods. It means that meat can be eaten which has taken several weeks to arrive from overseas in cold storage. Lamb produced in New Zealand, for example, is frozen before it is packed into the refrigerated holds of meat-carrying ships in which the temperature is held at -13°C to -12°C. Very little flavour is lost during the long voyage to Europe. If stored for longer than three months, flavour and tenderness is lost and the meat begins to deteriorate through surface dehydration.

For some kinds of food, such as wet fish, a damp atmosphere is maintained in cold stores. Poultry, on the other hand, are generally wet and warm when it arrives at the cold store. Dry, cold air is circulated so that excess moisture and heat are removed.

6.2 Definition of Freezing

Freezing will occur at different rates at different points in the piece or package of food. The location that cools slowest is known as the thermal centre and the freezing times are usually defined with reference to this point. The highest temperature at which ice crystals have a stable existence in a food material is conventionally known as the freezing point of that material. However, because of the nature of foodstuffs and the presence of water-soluble constituents, not all of the water solidifies at this temperature. Under equilibrium conditions and at a temperature just below the freezing point, a certain fraction of the water present remains in a fluid phase. This fraction falls when the temperature is lowered and the eutectic mixtures may separate from the unfrozen fluid, but unfrozen water is still present at comparatively low temperatures. Thus, it is not possible to define a clear endpoint to the freezing process.

The freezing time of a body may be defined as the time taken for its thermal centre to fall through the zone of maximum ice crystal formation. A body may be regarded as quick frozen if the period is two hours or less. The effective freezing time has been defined as the time required to reduce the temperature of the product from its initial average value to a given thermal centre. If the temperature is monitored at the thermal centre of a food as heat is removed, a characteristic curve shown in Figure 6.1 is obtained.

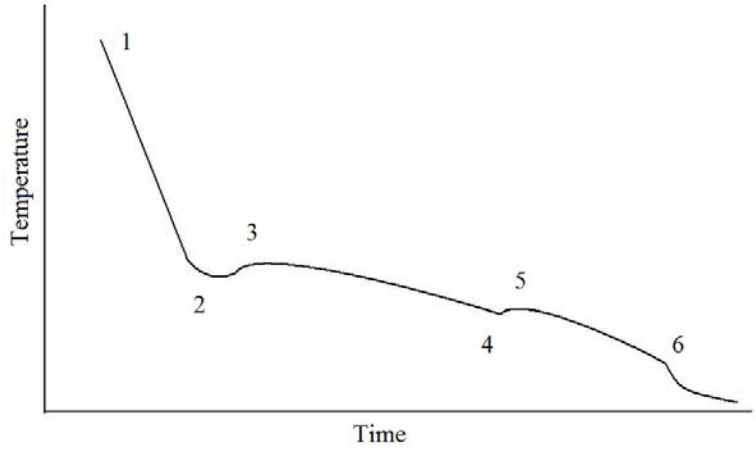


Figure 6.1 Freezing curve

The main features of the curve are:

AS The food is cooled to below its freezing point, which, with the exception of water, is always below 0°C. At point S the water remains liquid, although the temperature is below the freezing point. This phenomenon is known as super-cooling and may be as much as 10°C below the freezing point.

SB The temperature rises rapidly to the freezing point as ice crystals begin to form and latent heat of crystallisation is released.

BC Heat is removed from the food at the same rate as before. Latent heat is removed and ice forms, but the temperature remains almost constant. The freezing point is depressed by the increase in solute concentration in the unfrozen liquor, and the temperature therefore falls slightly. It is during this stage that most of the ice forms.

CD One of the solutes becomes supersaturated and crystallises out. The latent heat of crystallisation is released and the temperature rises to the eutectic temperature for that solute.

DE Crystallisation of water and solute continues. The total time taken for the freezing plateau is determined by the rate at which heat is removed.

EF The temperature of the ice-water mixture falls to the temperature of the freezer.

The total amount of heat to be removed by the freezing equipment consists of sensible heat change needed to cool the food to its freezing point, the latent heat of fusion involved in solidifying the liquid water in the food to ice and, finally, the sensible heat change to cool the frozen piece to its final temperature. Thus

$$Q = m\int c_{p(unfrozen)}dT_1 + m_w\lambda + m\int c_{p(frozen)}dT_2$$

There are various ways in which the specific heat of a food material can be expressed.

The change in enthalpy of cooled foods can alternatively be determined from experimental data which, by convention, the enthalpy is taken as 0 $kJ.kg^{-1}$ at -40°C. The specific enthalpy and thermophysical properties of some foods are given in Tables 6.1 and 6.2.

It is worth noting at this point that the thermal conductivity of ice is some five times greater than that of water and the thermal diffusivity is some ten times greater than that of water. It is therefore easier to propagate temperature in ice rather than water. The thermal conductivity for foods is less than that for ice because not all the food is ice and also food, generally, has a large voidage.

Example:

The latent heat of a food is found by experiment to be $2.3x10^5$ $J.kg^{-1}$. Estimate the moisture content of the food from this value.

Solution:

The latent heat of fusion of ice is 333 kJ.kg^{-1}. The moisture content is therefore found from

$$x_f = \frac{\lambda}{333} = \frac{2.3 \times 10^5}{333 \times 10^3} = 0.69$$

That is, a moisture content of 69%.

Table 6.1 Specific Enthalpy of Some Foods

	x_f	*Specific Enthalpy (kJ.kg^{-1})*									
	(%)	**-30°C**	**-20°C**	**-15°C**	**-10°C**	**-5°C**	**0°C**	**+5°C**	**+10°C**	**+20°C**	**+30°C**
Strawberries	89.3	16.7	38.9	53.5	72.8	109.2	364.0	343.1	401.2	440.1	482.8
Peaches	85.1	25.1	44.8	65.3	95.0	146.4	348.5	366.9	-	-	-
Orange Juice	89.0	16.7	38.5	55.6	75.3	118.8	356.9	377.0	400.8	437.6	479.1
Peas	75.8	17.6	43.5	60.7	86.6	144.8	312.5	330.5	347.3	384.5	390.4
Spinach	90.2	16.7	33.0	48.5	62.8	88.7	362.7	387.0	402.5	444.3	485.7
Carrots	87.5	25.5	45.2	60.2	102.5	124.3	358.1	376.1	-	-	-
Beef 5% fat	74.0	19.2	41.4	54.4	72.4	104.2	298.3	314.6	333.0	368.2	402.1
Pork 8% fat	70.0	19.2	40.6	53.5	70.7	100.8	281.5	298.3	315.9	351.4	385.3
Cod	80.3	20.1	42.2	56.1	71.5	105.0	322.6	341.0	360.2	381.2	434.3
Herring	63.8	20.1	42.2	56.1	73.2	101.2	278.2	296.2	314.2	348.9	382.4
Egg white	86.5	18.4	38.4	50.2	64.4	87.0	351.4	370.7	389.5	427.2	465.7
Egg yolk	50.0	18.4	38.9	50.6	64.8	84.5	228.4	246.4	268.2	303.7	334.3
Whole egg	74.0	18.4	38.9	52.3	66.1	85.8	308.4	328.4	349.4	387.0	441.4
Butter	16.0	16.7	35.1	45.6	58.1	74.9	139.3	157.7	179.5	228.0	264.0
Lard	0.00	14.6	31.0	40.6	51,9	64.4	82.4	107.5	125.1	151.8	195.4
White bread	35.0	17.5	35.1	46.4	66.5	109.6	125.5	137.6	150.6	174.0	201.2

Table 6.2 Thermophysical Properties of Some Foods (at ambient temperature)

	x_f (%)	α ($m^2.s^{-1}(x10^{-6})$)	ρ ($kg.m^{-3}$)	k ($kW.m^{-1}.K^{-1}$)	c_p ($kJ.kg^{-1}.K^{-1}$)
Apple juice	87.0	0.14	1000	0.559	3.86
Grape Juice	89.0	0.14	1000	0.481	3.59
Peaches`	85.1	0.14	960	0.526	3.91
Bananas	76.0	0.14	980	0.481	3.59
Potatoes	78.0	0.11	1355	0.498	3.64
Raisons	32.0	0.11	1380	0.376	2.48
Beef (5%)	74.0	0.13	1090	0.471	3.54
Chicken	75.0	0.13	1050	0.476	3.56
Pork	70.0	0.13	1030	0.456	3.49
Cod	80.3	0.12	1180	0.534	3.71
Lamb	72.0	0.13	1030	0.456	3.49
Turkey	74.0	0.13	1050	0.496	3.54
Veal	75.0	0.13	1060	0.470	3.56
Margarine	16.0	0.11	1000	0.233	2.08

Example:

Determine the total amount of heat to be removed during cooling and freezing of 10 kg of lean beef (5% fat) from an initial temperature of 20°C to a final temperature of -20°C.

Solution:

The heat to be removed is calculated from

$$Q = m(h_{20^\circ C} - h_{-20^\circ C})$$

From Table 6.1 this is

$$Q = 10 \times (368.2 - 41.4) = 3268kJ$$

Alternatively, an empirical relationship for specific enthalpy for beef is given by

$$h = 216.9 + 2.90T + 8.25 \times 10^{-3} T^2 + 73.3 \tan^{-1}(1.76(T + 1.7))$$

Where T is the temperature in °C. Thus

$$Q = m(h_{20^oC} - h_{-20^oC}) = 10 \times (391.4 - 49.3) = 3421kJ$$

This is slightly higher value. The empirical relation which fits experimental data well is shown in Figure 6.2.

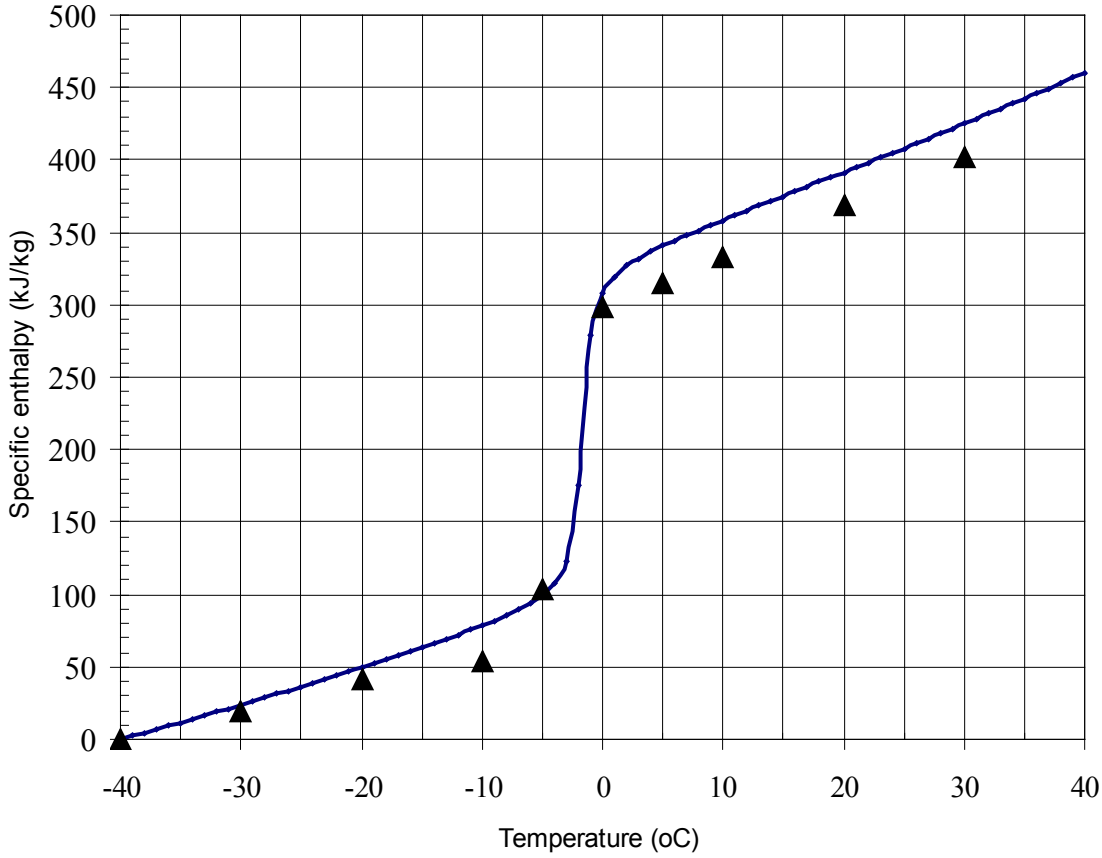


Figure 6.2 Specific Enthalpy of Lean Beef

Pre-cooling

The rate of heat loss from a body of food during the pre-cooling period by convection is given by

$$-mc_p \frac{dT}{dt} = hA(T - T_o)$$

Where T_o is the temperature of the cooling medium. The time taken to cool the food from an initial temperature, T_1, down to the freezing point, T_2, can be determined by rearranging the equation to

$$\int_0^t dt = \frac{-mc_p}{hA}\int_{T_i}^{T_2}\frac{dT}{T-T_o}$$

Completing the integration to gives

$$t = \frac{mc_p}{hA}\ln\left(\frac{T_1-T_o}{T_2-T_o}\right)$$

Example:

A 5 kg block of cod with a moisture content of 80.3% w/w is to be frozen in air at -20°C. The surface area of the block is 0.2 m^2 and the heat transfer coefficient is 30 $W.m^{-2}.K^{-1}$. Determine the time for the block to reach its freezing point of -2°C.

Solution:

Using data in Table 6.2, the time for the block to reach its freezing point is therefore determined from

$$t = \frac{mc_p}{hA} \ln\left(\frac{T_1 - T_o}{T_2 - T_o}\right) = \frac{5 \times 3710}{30 \times 0.2} \ln\left(\frac{5 - -20}{-2 - -20}\right) = 1016s$$

or about 17 minutes.

6.1.1 Quick-Freezing

As an advance on cold air storage, "quick-freezing" was developed the result of the early pioneering work of Clarence Birdseye in the 1930s in which he noticed how the Eskimos of Arctic Canada kept food in the intense cold of the open air for several months and yet were able to eat it as fresh when it was thawed. It was found that food that is frozen quickly and kept at a sufficiently low temperature loses little flavour or textural properties and can still be fresh many months later.

When food is frozen slowly, large ice crystals form in the cells of the food. The crystals rupture the cell walls as they grow. When the food is thawed the water drains away carrying salts and other minerals with it. The food consequently loses it flavour and value. In the "quick-freeze" method the ice crystals are formed much more quickly and are much smaller. All the moisture in the food freezes before the crystals have had time to reach a size sufficient to rupture the cell walls. When the food is thawed no moisture is lost.

6.1.2 Freezing Kinetics

Formulae are available for estimating the effective freezing time, although calculations involving unsteady state heat transfer with a change of phase are not always straightforward. Such formulae are usually based on the assumptions that the body to be frozen is initially at a uniform temperature and is cooled by a constant temperature medium. It is also assumed that the body has a constant thermal conductivity and the specific heat are different for the frozen and unfrozen states, has a constant density that does not vary with temperature or alter during the freezing process and that there is a definite freezing point at which all the latent heat of fusion is liberated.

If the body to be frozen is initially at its freezing point and that there is no pre-cooling period, hence no heat flows in the unfrozen material, the calculation of its freezing time is comparatively simple. Further simplification occurs if the material at the thermal centre at the end of the freezing process is assumed to be frozen, but still at its freezing point. The freezing time calculated on these assumptions may be termed the calculated freezing time. The effective freezing time can be estimated from the calculated freezing time by applying corrections to allow any pre- and post-cooling.

Formulae for the calculated freezing times can be simplified by making use of three dimensionless groups. Two of these, the Biot (Bi) and Fourier (Fo) numbers, are commonly used for unsteady state heat transfer and are given by:

$$Bi = \frac{hl}{k}$$

and

$$Fo = \frac{\alpha t}{l^2}$$

where h is the surface heat transfer coefficient at the surface of the body, l is the characteristic dimension of the body, k is the thermal conductivity of the frozen body and α is the thermal diffusivity of the body given by:

$$\alpha = \frac{k}{\rho c_p}$$

where ρ is the density and c_p is the specific heat of the food.

It is often important to determine the temperature at the centre of a body in the final stages of heating and cooling. When a solid body changes temperature from T_1 to T_0 it is convenient to express the temperature, T, of a point within it at time t during the change as a dimensionless temperature, V, as

$$V = \frac{T - T_o}{T_1 - T_o}$$

Clearly V will have an initial value of 1.0 and will tend to zero as the change progresses. Formulae for V are conveniently expressed in the terms of the Bi and Fo numbers. Expressions giving V as a function of time are available but are cumbersome. Charts are available for determining V at certain points in slabs, rods, cylinders, spheres and brick-shaped bodies.

In calculating the Biot and Fourier numbers, the characteristic dimension is the shortest distance from the thermal centre to the surface of the body being frozen. The calculated freezing time and the thermal constants used are those for the frozen material. Figures 6.3, 6.4 and 6.5 are used to determine the temperature of a food found from the dimensionless temperature, V, and Fourier number.

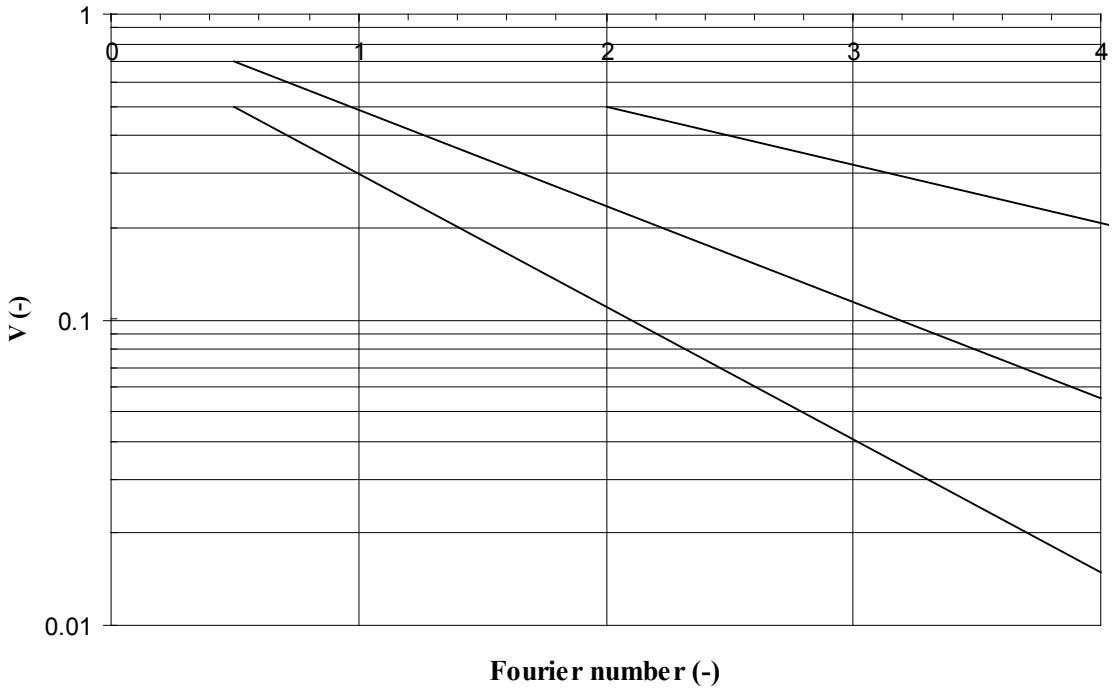


Figure 6.3 Temperature for the centre of an infinite slab. The lines are for 1/Bi=0.5, 1.0 and 2.0

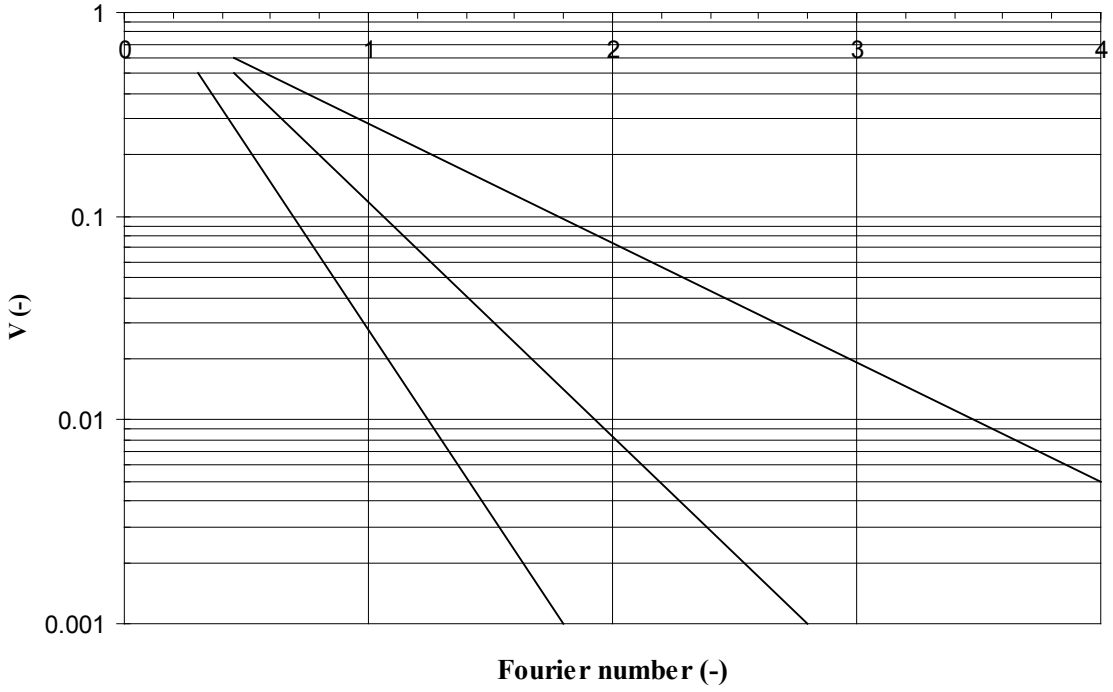


Figure 6.4 Temperature for the centre of a sphere. The lines are for 1/Bi=0.5, 1.0, and 2.0

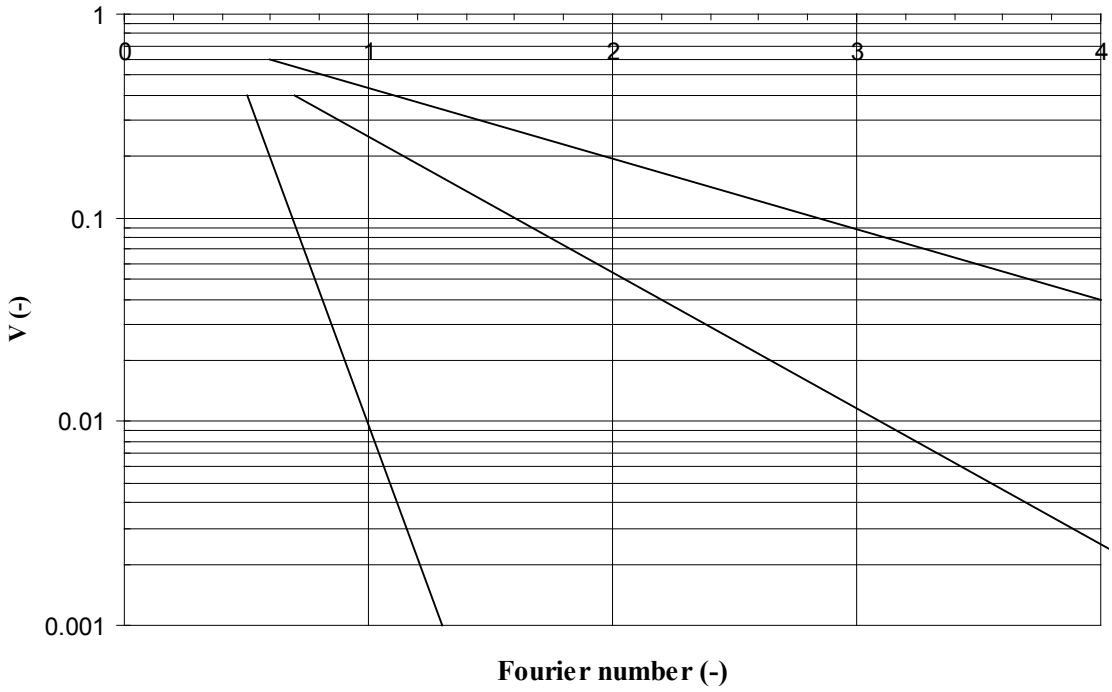


Figure 6.5 Temperature for the centre of a cylinder. The lines are for 1/Bi=0.5, 1.0, and 2.0

6.2 Freezing of a Slab

To determine the time taken to freeze a semi-infinite slab of food, assume that the foodstuff is a finite slab of thickness *2l* with a heat transfer coefficient at both surfaces as shown. The slab is considered to be semi-infinite since the width far exceeds the thickness so end effects are not needed to be taken into consideration.

Now assume also that the slab is already at its freezing point and that the material does not change in density and a phase change takes place at a specific phase transition temperature. Consider one face of the slab where a thickness *dx* is frozen in time *dt*.

The rate of heat release unit area, *q*, (flux) at the freezing front is therefore

$$q = \rho\lambda \frac{dx}{dt}$$

The rate of heat transfer by conduction per unit area through the frozen layer is given by

$$q = \frac{k}{x}(T_o - T_1)$$

where *k* is the thermal conductivity of the frozen foodstuff and *x* is the thickness of ice formed at the surface. Thus

$$\frac{k}{x}(T_o - T_1) = \rho\lambda \frac{dx}{dt}$$

The rate of convection from the surface per unit area is given by

$$q = h(T_1 - T_2)$$

So

$$h(T_1 - T_2) = \rho\lambda \frac{dx}{dt}$$

Rearranging the two equations

$$T_1 - T_2 = \frac{\rho\lambda}{h}\frac{dx}{dt}$$

$$T_0 - T_1 = \frac{\rho\lambda x}{k}\frac{dx}{dt}$$

Addition gives

$$T_0 - T_2 = \frac{\rho\lambda}{h}\frac{dx}{dt} + \frac{\rho\lambda x}{k}\frac{dx}{dt}$$

Therefore

$$\frac{\Delta T}{\rho\lambda}dt = \frac{dx}{h} + \frac{xdx}{k}$$

where ΔT is the difference in temperature between the freezing medium and the freezing point of the foodstuff. Integrating over the half-thickness of the slab

$$\frac{\Delta T}{\rho\lambda}\int_0^t dt = \int_0^l \frac{dx}{h} + \int_0^l \frac{xdx}{k}$$

gives

$$t = \frac{\rho\lambda}{\Delta T}\left(\frac{l}{h} + \frac{l^2}{2k}\right)$$

which can further be written as

$$t = \frac{\rho\lambda l^2}{k\Delta T}\left(\frac{k}{hl} + \frac{1}{2}\right)$$

Multiplying both sides by $k/\rho c_p l^2$ gives

$$\frac{kt}{\rho c_p \Delta T} = \frac{\lambda}{c_p \Delta\theta}\left(\frac{k}{hl} + \frac{1}{2}\right)$$

That is, in dimensionless form:

$$Fo = Ko\left(\frac{1}{Bi} + \frac{1}{2}\right)$$

This is known as the Plank equation after originally being proposed by R.Z. Plank in 1913 in which Ko is the Kossovitch number, given as

$$Ko = \frac{\lambda}{c_p \Delta T}$$

Example:

Sliced pork is quick frozen in a continuous blast freezer using chilled air. The air with a mass flow of 20 kg. $m^{-2}.s^{-1}$ is passed through a stack of trays at -34°C in a duct of mean hydraulic diameter of 0.1m. Assuming that the pork slices, which have a slab of thickness 1.0 cm, are considered to be infinite in each direction perpendicular to the heat flow, that steady state conditions exist in the blast freezer and that heat is extracted equally from both sides of the slab, calculate the freezing time using the following data:

Pork:		Air	
Density	1030 $kg.m^{-3}$	Viscosity	$1.6x10^{-5}$ $kg.m^{-1}.s^{-1}$
Thermal conductivity	0.456 $W.m^{-1}.K^{-1}$	Specific heat	1005 $J.kg^{-1}.K^{-1}$
Latent heat of fusion	$2.3x10^{5}$ $J.kg^{-1}$	Thermal conductivity	0.0242 $W.m^{-1}.K^{-1}$
Freezing point	$-2^{o}C$		

Solution:

The heat transfer coefficient is obtained from the Dittus-Boelter equation for turbulent flow

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$$

Where the Reynolds number is given by

$$\mathrm{Re} = \frac{Gd_m}{\mu} = \frac{20 \times 0.1}{1.6 \times 10^{-5}} = 125{,}000$$

and the Prandtl number is given by

$$\mathrm{Pr} = \frac{c_p \mu}{k} = \frac{1005 \times 1.6 \times 10^{-5}}{0.0242} = 0.66$$

Nusselt number is therefore

$$Nu = \frac{h d_m}{k} = \frac{h \times 0.1}{0.0242} = 0.023 \times 125000^{0.8} \times 0.66^{0.4} = 232.8$$

Solving gives a heat transfer coefficient of 56.3 $W.m^{-2},K^{-1}$. The freezing time for an infinite slab is therefore

$$t = \frac{\rho \lambda l^2}{k \Delta T}\left(\frac{k}{hl} + \frac{1}{2}\right) = \frac{1030 \times 2.3 \times 10^5 \times 0.005^2}{0.456 \times 32} \times \left(\frac{0.456}{56.3 \times 0.005} + \frac{1}{2}\right) = 860s$$

or about 14½ minutes.

6.3 General Case for Freezing

The Plank equation can be developed from first principles for other geometries such as cylinders and spheres. Plank's work may by summarised in the dimensionless form

$$\frac{Fo}{Ko} = D\left(\frac{1}{Bi} + G\right)$$

where the constants *D* and *G* are determined by the geometry of the body being frozen. *G* takes the value ½ for the infinite slab, infinite cylinder and sphere. The constant *D* is given by

$$D = \frac{V}{al}$$

where V is the volume of the body and a is the area of its cooled surface. For the infinite slab, infinite cylinder and sphere D takes the values 1, ½ and ⅓, respectively.

In practical applications it is often difficult to decide on an appropriate value for the heat transfer coefficient, h. For the blast freezing of unpacked food heat transfer coefficients can be calculated from standard formulae.

Example:

Determine the geometric constant D for the freezing of spherical shaped foods such as peas.

Solution:

The geometric index is given by

$$D = \frac{V}{al} = \frac{\frac{4}{3}\pi r^3}{4\pi r^2 \times r} = \frac{1}{3}$$

6.4 Chilling

The chilling of foods is a process by which the temperature of a food is reduced to a desired holding temperature just above the freezing point and is usually in the range of -2°C to 2°C. The effect of chilling is to slow the rate of deterioration and reactions that are temperature dependent. The chilling of food therefore extends shelf-life.

The rate of chilling is governed by the laws of (unsteady state) heat transfer. To determine the rate of chilling, it is necessary to evaluate the surface heat transfer coefficient, the resistance offered to heat flow by any packing material and the unsteady state conduction.

Although the shape and geometry of most foods are not regular, they often approximate to the shape of slabs, bricks, spheres and cylinders.

Example:

Plot the variation of thermal conductivity for carrots if below the freezing point of -1oC the conductivity can be given by

$$k = 1.26 - 0.0011T + 0.8624/T$$

and above the freezing point, is given by

$$k = 0.551 + 0.0011T$$

Solution:

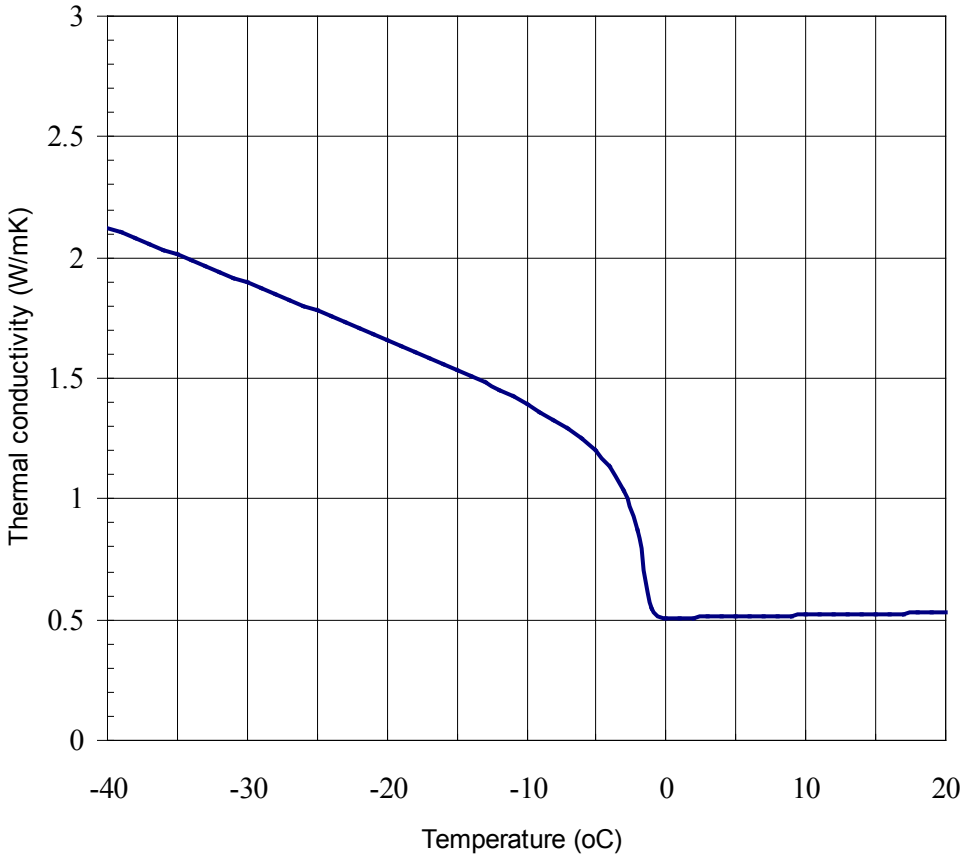


Figure 6.6 Thermal conductivity of carrots

Note the rapid decline towards the freezing point. This trend is typical for most foods.

Example:

Determine the time taken to chill apples with a diameter of 7 cm and initial temperature of 25°C to a core temperature of 5°C using air at a temperature of -1°C. The surface heat transfer coefficient is 30 $W.m^{-2}.K^{-1}$. The density of the apples is 920 $kg.m^{-3}$ and their specific heat is 3.6 $kJ.kg^{-1}.K^{-1}$ and thermal conductivity is 0.5 $W.m^{-1}.K^{-1}$.

Solution

The Biot number is

$$Bi = \frac{hr}{k} = \frac{30 \times 0.035}{0.5} = 2.1$$

The reciprocal is therefore

$$\frac{1}{Bi} = \frac{1}{2.1} = 0.48$$

The dimensionless temperature is

$$\frac{T - T_o}{T_1 - T_o} = \frac{5 - (-1)}{25 - (-1)} = 0.23$$

From Figure 6.4, the Fourier number is

$$Fo = 0.46 = \frac{kt}{\rho c_p r^2}$$

Rearranging

$$t = \frac{\rho c_p r^2 Fo}{k} = \frac{930 \times 3600 \times 0.035^2 \times 0.46}{0.5} = 3773s$$

or about 1 hour and 3 minutes. It is worth noting that a complete analysis should take into account the mass transfer from the surface of the food in which moistures is drawn from the surface effectively drying the food.

Example:

Rectangular blocks of food 2 cm high, 5 cm deep and 8 cm broad are to be frozen in a continuous blast-freezing tunnel on a belt 1.5 m wide. The blocks are to be placed on the belt, which offers negligible resistance to heat flow to the face in contact with it. The blocks are to be placed so that the 8 cm breadth is across the belt while the 5 cm depth is along the belt in the direction of travel.

Three forms of placement are possible, with the blocks being packed together in a slab, lined up across the belt in bars 5cm apart, or individually spaced 5cm apart as shown below in Figure 6.7:

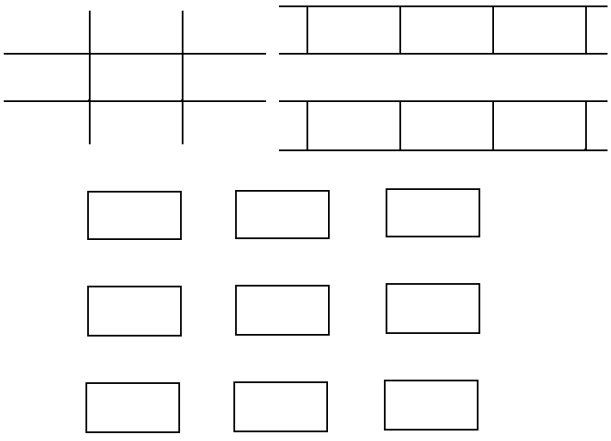


Figure 6.7 Possible arrangements of food on a belt

Assuming that the heat transfer coefficient at every exposed face is the same and is not influenced by the arrangement, determine which arrangement will give the highest plant throughput. The second geometric coefficient in Plank's equation, G, may be assumed to be equal to ½ in each case.

Solution:

In each case the time for freezing for a slab is given by

$$t = \frac{D\rho\lambda l^2}{k\Delta T}\left(\frac{k}{hl} + \frac{1}{2}\right)$$

Thus for the three cases, the time is proportional to the geometric index, D. So

$$D_1 = \frac{V}{al} = \frac{2\times5\times8}{2\times5\times8\times1} = 1.000$$
$$D_2 = \frac{V}{al} = \frac{2\times5\times8}{2\times(5\times8+2\times8)\times1} = 0.714$$
$$D_1 = \frac{V}{al} = \frac{2\times5\times8}{2\times(5\times8+2\times8+5\times2)\times1} = 0.606$$

This shows that the individual blocks freezing 39% quicker than those closely packed. However, the number of blocks spread over the belt (taking a 1.0 length of belt) is

$$N_1 = 18\times20 = 360$$
$$N_1 = 18\times10 = 180$$
$$N_1 = 12\times10 = 120$$

The relative throughput is therefore

$$\frac{N_1}{D_1} : \frac{N_2}{D_2} : \frac{N_3}{D_3} = \frac{360}{1} : \frac{180}{0.714} : \frac{110}{0.606} = 360 : 252 : 181$$

The best arrangement is therefore to compress the blocks together in spite of the slower freezing time.

Example:

Sliced potato fries 1cm by 1cm with a mean length of 6cm are individually quick frozen in a blast freezer operating at -30°C and with a heat transfer coefficient of 120 $W.m^{-1}.K^{-1}$. If the fries are already at their freezing point determine the expected freezing time.

Data:

Conductivity of potato	0.498 $W.m^{-1}.K^{-1}$
Density of potato	1055 $kg.m^{-3}$
Freezing point of potato	-1°C
Latent heat of fusion	$2.7x10^5$ $J.kg^{-1}$.

Solution:

The geometric index used in the Plank equation is

$$D = \frac{V}{al} = \frac{0.01 \times 0.01 \times 0.06}{(2 \times 0.01 \times 0.01 + 4 \times 0.06 \times 0.01) \times 0.005} = 0.46$$

The freezing of the fry is therefore

$$t = \frac{D\rho\lambda l^2}{k\Delta T}\left(\frac{k}{hl}+\frac{1}{2}\right) = \frac{0.46\times1055\times2.7\times10^5\times0.005^2}{0.498\times29}\left(\frac{0.498}{120\times0.005}+\frac{1}{2}\right) = 302s$$

The fries take approximately 5 minutes to freeze.

Example:

Show from first principles that the heat transfer for the freezing of an infinite cylinder can be expressed in the dimensionless form:

$$Fo = \frac{Ko}{2}\left(\frac{1}{Bi}+\frac{1}{2}\right)$$

Solution:

Assume that the foodstuff is a semi-infinite cylinder of radius R with heat transfer at the surfaces. Assume also that the foodstuff is at its freezing point and that the material does not change in density and a phase change takes place at a specific phase transition temperature. The rate of heat release unit area, q, (flux) at the freezing front at radius r is therefore

$$q = \rho\lambda 2\pi r\frac{dr}{dt}$$

The rate of heat transfer by conduction per unit area through the frozen layer is given by

$$q = \frac{2\pi k(\theta_o-\theta_1)}{\ln\left(\frac{R}{r}\right)}$$

where k is the thermal conductivity of the frozen foodstuff and r is the radius of the ice front. Thus

$$\frac{2\pi k(\theta_o - \theta_1)}{\ln\left(\frac{R}{r}\right)} = \rho\lambda 2\pi r \frac{dr}{dt}$$

The rate of convection from the surface per unit area is given by

$$q = 2\pi Rh(\theta_1 - \theta_2)$$

Thus

$$2\pi Rh(\theta_1 - \theta_2) = \rho\lambda 2\pi r \frac{dr}{dt}$$

Rearranging the two equations

$$\theta_1 - \theta_2 = \frac{\rho\lambda r}{Rh}\frac{dr}{dt}$$

$$\theta_0 - \theta_1 = \frac{\rho\lambda r}{k}\ln\left(\frac{R}{r}\right)\frac{dr}{dt}$$

Addition and rearranging gives

$$\frac{\Delta\theta}{\rho\lambda}dt = \frac{rdr}{Rh} + \frac{\ln Rrdr}{k} - \frac{\ln r.rdr}{k}$$

where $\Delta\theta$ is the difference in temperature between the freezing medium and the freezing point of the foodstuff. Integrating over the radius of the cylinder

$$\frac{\Delta\theta}{\rho\lambda}\int_o^t dt = \int_0^R \frac{rdr}{Rh} + \int_0^R \frac{\ln Rrdr}{k} - \int_0^R \frac{\ln r.rdt}{k}$$

gives

$$t = \frac{\rho\lambda}{\Delta\theta}\left(\frac{R^2}{2Rh} + \frac{\ln RR^2}{2k} - \frac{\ln RR^2}{2k} + \frac{R^2}{4k}\right)$$

which can be reduced to

$$t = \frac{\rho\lambda}{\Delta\theta}\left(\frac{R}{2h} + \frac{R^2}{4k}\right)$$

or further

$$t = \frac{\rho\lambda R^2}{2k\Delta\theta}\left(\frac{k}{hR} + \frac{1}{2}\right)$$

Rearranging, the freezing time, *t*, is

$$\frac{kt}{\rho c_p R^2} = \frac{k\rho\lambda R^2}{2k\rho c_p R^2 \Delta\theta}\left(\frac{k}{hR} + \frac{1}{2}\right)$$

In dimensionless form using the Fourier number

$$Fo = \frac{Ko}{2}\left(\frac{1}{Bi} + \frac{1}{2}\right)$$

Example:

After production of the meat into skins, sausages are immediately frozen in a blast freezer for storage and transportation purposes. The sausages have a diameter of 2 cm and are made from lean meat with a moisture content of 55% and density of 1120 kg.m^{-3}. The sausages have a thermal conductivity, *k*, of 0.6 W.m^{-1}.K^{-1} and the blast freezer operates at a temperature of -18°C and provides a surface heat transfer coefficient of 120 W.m^{-2}.K^{-1}. blast freezer. If the sausages enter the blast freezer at their freezing point of -2°C, determine their freezing time.

Solution:

The freezing time, *t*, for semi-infinite cylindrical geometry is given by:

$$t = \frac{\rho\lambda R^2}{2k\Delta T}\left(\frac{k}{hR} + \frac{1}{2}\right)$$

For the supplied data:

$$t = \frac{1120 \times 333000 \times 0.55 \times 0.01^2}{2 \times 0.6 \times 16}\left(\frac{0.6}{120 \times 0.01} + \frac{1}{2}\right) = 1067s$$

Example:

Explain what it meant but the term "thermal centre" of a body being frozen. Discuss the interpretation of temperature measurements made at the thermal centre.

Solution:

The thermal centre is the slowest point of a food to freeze and is not necessarily the geometric centre of the food.

Example:

A slab of food of thickness 2l, is to be frozen from both sides, with heat transfer coefficient h_1 at one face and h_2 at the other ($h_1 > h_2$). Assuming the validity of Plank's equation for freezing times, determine the displacement Δ from the geometric centre of the food at which the food finally freezes.

Solution:

The combined convection and conduction heat fluxes for both faces are

$$\frac{\Delta T}{\rho\lambda}\int_0^t dt = \int_0^{l+\Delta}\frac{dx}{h_1} + \int_0^{l+\Delta}\frac{xdx}{k}$$

and

$$\frac{\Delta T}{\rho\lambda}\int_0^t dt = \int_0^{l-\Delta}\frac{dx}{h_2} + \int_0^{l-\Delta}\frac{xdx}{k}$$

Integrating both equations gives

$$t = \frac{\rho\lambda}{\Delta T}\left(\frac{l+\Delta}{h_1} + \frac{(l+\Delta)^2}{2k}\right) = \frac{\rho\lambda}{\Delta\theta}\left(\frac{l-\Delta}{h_2} + \frac{(l-\Delta)^2}{2k}\right)$$

Expanding and ignoring small terms reduces to

$$\Delta = \frac{lk(h_1 - h_2)}{k(h_1 + h_2) + 2l(h_1 h_2)}$$

Example:

One tonne of lamb loin is to be frozen from an initial temperature of 30°C to a final temperature of -30°C. The lamb has a moisture content of 65% and the freezing point may be taken as -2°C. The specific enthalpy, h (kJ.kg^{-1}) for lamb can be given by

$$h = 217.6 + 3.24T + 0.018T^2 + 75.7\tan^{-1}(0.944(T+2.1))$$

where T is temperature (°C).

Solution:

Using the relationship for specific enthalpy, h (kJ.kg^{-1}) for lamb:

$$h_{30^oC} = 217.6 + 3.24 \times 30 + 0.018 \times 30^2 + 75.7 \tan^{-1}(0.944(30 + 2.1)) = 468 kJ.kg^{-1}$$
$$h_{-30^oC} = 217.6 + 3.24 \times -30 + 0.018 \times -30^2 + 75.7 \tan^{-1}(0.944(-30 + 2.1)) = 16.9 kJ.kg^{-1}$$

The heat removed is therefore

$$Q = m(h_{30^oC} - h_{30^oC}) = 1000 \times (468 - 16.9) = 451.1 kJ$$

Example:

A ham burger manufacturer produces fresh burgers made from pork with 8% fat and moisture content of 70%. These are then frozen and packaged. The burger freezing process involves a continuous belt blast freezer upon which burgers 10 cm in diameter and 0.5 cm thick are frozen in rows of 10 burgers across the width of the belt. There is 10 cm between the burger centres along the length of the belt and the belt is perforated so that the freezing may be assumed to take place equally from both sides. The burgers are initially at their freezing point of -2°C and emerge from the freezer with their centres just frozen. Determine the belt speed (cm.s^{-1}) and production rate (kg.s^{-1}) if the length of the belt covered with burgers is 20 m.

Data:

Density of frozen burgers	1100 kg.m^{-3}
Air temperature	251 K
Heat transfer coefficient	120 W.m^{-2}.K^{-1}
Thermal conductivity of frozen burgers	1.3 W.m^{-1}.K^{-1}

Solution:

The burgers are assumed to be infinite slabs since their radius is considerably greater than their thickness. The time for freezing time is therefore

$$t = \frac{\rho\lambda l^2}{k\Delta T}\left(\frac{k}{hl}+\frac{1}{2}\right) = \frac{1100\times 333000\times 0.7\times 0.0025^2}{1.3\times 20}\left(\frac{1.3}{120\times 0.0025}+\frac{1}{2}\right) = 298s$$

For a 20m belt, the belt speed is therefore 20/298=0.0067 ms^{-1}.

The mass of a burger is

$$m = \rho V = \rho\frac{\pi d^2}{4}2l = 1100\times\frac{3.14\times 0.1^2}{4}\times 2\times 0.005 = 0.043kg$$

With 100 burgers per 1.0 m length coverage of belt, the production rate is therefore

$$4.32\times 0.067 = 0.289kg.s^{-1}$$