2
Thermal Processing

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2.1
Introduction

Thermal processing involves heating food, either in a sealed container or by passing it through a heat exchanger, followed by packaging. It is important to ensure that the food is adequately heat treated and to reduce postprocessing contamination (ppc). The food should then be cooled quickly and it may require refrigerated storage or be stable at ambient temperature. The heating process can be either batch or continuous. In all thermal processes, the aim should be to heat and cool the product as quickly as possible. This has economic implications and may also lead to an improvement in quality. Heat or energy (J) is transferred from a high to a low temperature, the rate of heat transfer being proportional to the temperature difference. Therefore, high temperature driving forces will promote heat transfer. SI units for rate of heat transfer (J s^{-1} or W) are mainly used but Imperial units (BTU h^{-1}) may also be encountered [1]. The heating medium is usually saturated steam or hot water. For temperatures above 100 °C, steam and hot water are above atmospheric pressure. Cooling is achieved using either mains water, chilled water, brine or glycol solution. Regeneration is used in continuous processes to further reduce energy utilisation (see Section 2.2.3).

2.1.1
Reasons for Heating Foods

Foods are heated for a number of reasons, the main one being to inactivate pathogenic or spoilage microorganisms. It may also be important to inactivate enzymes, to avoid the browning of fruit by polyphenol oxidases and minimise flavour changes resulting from lipase and proteolytic activity. The process of heating a food also induces physical changes and chemical reactions, such as starch gelatinisation, protein denaturation or browning, which in turn affect the sensory characteristics, such as colour, flavour and texture, either advanta-

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geously or adversely. For example, heating pretreatments are used in the production of evaporated milk to prevent gelation and age-thickening and for yoghurt manufacture to achieve the required final texture in the product. Heating processes may also change the nutritional value of the food.

Thermal processes vary considerably in their intensity, ranging from mild processes such as thermisation and pasteurisation through to more severe processes such as in-container sterilisation. The severity of the process affects both the shelf life and other quality characteristics.

Foods which are heat-treated can be either solid or liquid, so the mechanisms of conduction and convection may be involved. Solid foods are poor conductors of heat, having a low thermal conductivity, and convection is inherently a much quicker process than conduction. Fluids range from those having a low viscosity (1–10 mPa s), through to highly viscous fluids; and the presence of particles (up to 25 mm in diameter) further complicates the process, as it becomes necessary to ensure that both the liquid and solid phases are at least adequately and if possible equally heated. The presence of dissolved air in either of the phases is a problem as it becomes less soluble as temperature increases and can come out of solution. Air is a poor heat transfer fluid and hot air is rarely used as a heating medium. Attention should be paid to removing air from steam e.g. venting of steam retorts and removing air from sealed containers (exhausting).

Heating is also involved in many other operations, which will not be covered in such detail in this chapter, such as evaporation and drying (see Chapter 3). It is also used for solids; in processing powders and other particulate foods: for example extrusion, baking (see Chapter 8) and spice sterilisation.

2.1.2 Safety and Quality Issues

The two most important issues connected with thermal processing are *food safety* and *food quality*. The major safety issue involves inactivating pathogenic microorganisms which are of public health concern. The World Health Organisation estimates that there are over 100 million cases of food poisoning each year and that one million of these result in death. These pathogens show considerable variation in their heat resistance: some are heat-labile, such as *Campylobacter*, *Salmonella*, *Lysteria* and of more recent concern *Escherichia coli* 0157, which are inactivated by pasteurisation, while of greater heat resistance is *Bacillus cereus*, which may survive pasteurisation and also grow at low temperatures. The most heat-resistant pathogenic bacterial spore is *Clostridium botulinum*. As well as these major foodborne pathogens, it is important to inactivate those microorganisms which cause food spoilage, such as yeasts, moulds and gas-producing and souring bacteria. Again there is considerable variation in their heat resistance, the most heat-resistant being the spores of *Bacillus stearothermophilus*. The heat resistance of any microorganism changes as the environment changes, for example pH, water activity or chemical composition changes; and foods themselves provide such a complex and variable environment. New micro-

organisms may also be encountered, such as *Bacillus sporothermodurans* (see Section 2.5.1). Therefore it is important to be aware of the type of microbial flora associated with all raw materials which are to be heat-treated.

After processing, it is very important to avoid reinfection of the product, generally known as ppc, which can cause problems in both pasteurisation and sterilisation. Therefore, raw materials and finished products should not be allowed in close proximity to each other. Other safety issues are concerned with natural toxins, pesticides, herbicides, antibiotics and growth hormones and environmental contaminants. Again, it is important that steps are taken to ensure that these do not finish up in the final product. Recently, there have been some serious cases of strong allergic reactions, with some deaths, shown by some individuals to foods such as peanuts and shellfish. These are all issues which also need to be considered for heat-treated foods.

Quality issues revolve around minimising chemical reactions and loss of nutrients and ensuring that sensory characteristics (appearance, colour, flavour and texture) are acceptable to the consumer. Quality changes, which may result from enzyme activity, must also be considered. There may also be conflicts between safety and quality issues. For example, microbial inactivation and food safety is increased by more severe heating conditions, but product quality in general deteriorates. To summarise, it is important to understand reaction kinetics and how they relate to:

- microbial inactivation
- chemical damage
- enzyme inactivation
- physical changes.

2.1.3 Product Range

The products covered in this book include those which can be filled into containers and subsequently sealed and heat-treated and those which can be processed by passing them through a continuous heat exchanger. This latter category includes milks and milk-based drinks, fruit and vegetable juices, purees, soups and sauces (both sweet and savoury) and a range of products containing particulate matter, up to about 25 mm diameter. There are two distinct market sectors. The first involves those products which are given a mild heat treatment and then kept refrigerated throughout storage: these are covered in Section 2.4. The second involves those which are sterilised and stored at ambient temperature: these are covered in Section 2.5. The relative importance of these two sectors varies from country to country for different products and from country to country for the same product. For example, in England and Wales, pasteurised milk, which is stored chilled, accounts for about 87% of liquid milk consumption, whilst UHT and sterilised milk accounts for about 10%. However, UHT milk accounts for a much greater proportion of milk consumed in other coun-

tries, for example France (78%) and Germany (58%), so it is important to note that there are regional differences and preferences [2].

In general, heat processing eliminates the need to use further additives to extend the shelf life, although additives may help improve the sensory characteristics or make processes less susceptible to fouling. In addition to reactions taking place during the heat treatment, chemical, enzymatic and physical changes will continue to take place during storage. Microorganisms which survive the heat treatment may also grow if conditions are favourable. Pasteurised products are normally kept refrigerated during storage to retard microbial growth; and low temperatures must be maintained throughout the Cold Chain. In contrast, sterilised products are not normally refrigerated and are stored at ambient temperature. This may vary considerably throughout the world, ranging from below 0 °C to above 50 °C. All the reactions mentioned above are temperature-dependent and considerable changes may take place during the storage period. One example is browning of milk and milk products, which is very significant after 4 months storage at 40 °C. Changes during storage are discussed in more detail for pasteurised products in Section 2.4.3 and for sterilised products in Section 2.7.1.

2.2 Reaction Kinetics

2.2.1 Microbial Inactivation

All thermal processes involve three distinct periods: a heating period, holding period and cooling period. In theory, all three periods may contribute to the reactions taking place, although in situations where heating and cooling are rapid, the holding period is the most significant. However, procedures are needed to evaluate each of these periods individually, to determine the overall effect. By far the easiest to deal with is the holding period, as this takes place at constant temperature. Then it needs to be established how reaction rates are affected by changes in temperature during heating and cooling. To simplify the analysis, microbial inactivation is first measured at constant temperature. This is usually followed by observing how microbial inactivation changes with temperature.

2.2.2 Heat Resistance at Constant Temperature

When heat inactivation studies are carried out at constant temperature, it is often observed that microbial inactivation follows first order reaction kinetics i.e. the rate of inactivation is directly proportional to the population. This can be illustrated by plotting the log of the population against time (see Fig. 2.1) and finding that there is a straightline relationship.

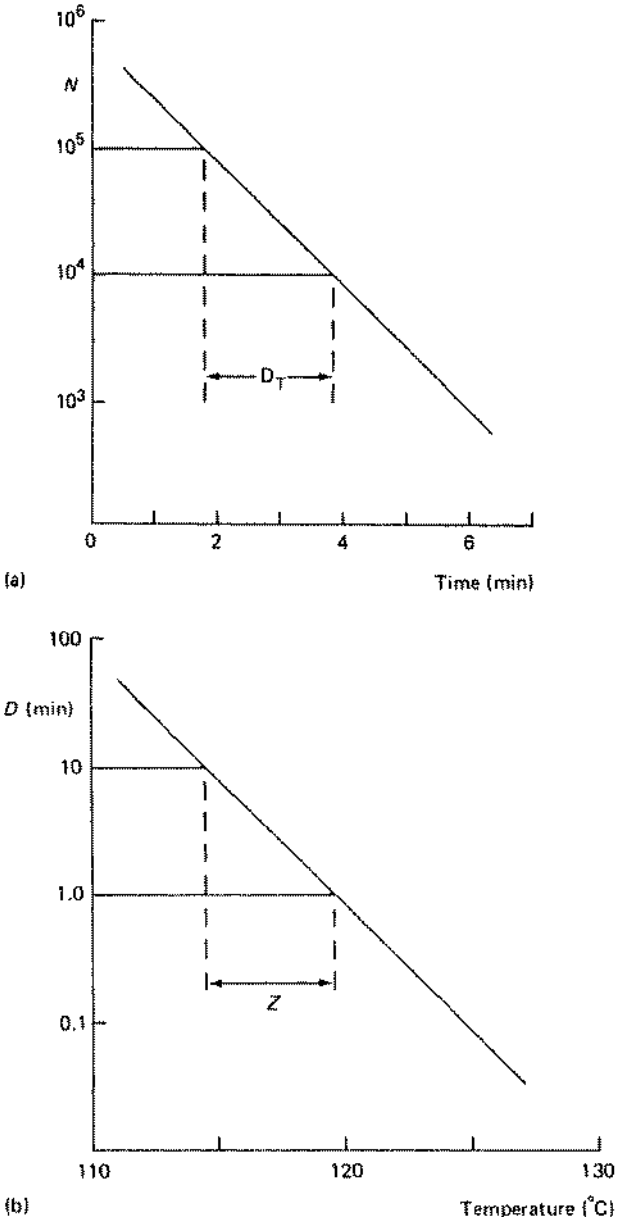


Fig. 2.1 (a) Relationship between the population of microorganisms and time at a constant heating temperature, (b) relationship between the decimal reduction time and temperature, to determine the *z* value; from [1] with permission.

The heat resistance of an organism is characterised by its decimal reduction time (D_T), which is defined as the time required to reduce the population by 90% or by one order of magnitude or one log cycle, i.e. from 10^4 to 10^3, at a constant temperature, *T*.

Every microorganism has its own characteristic heat resistance and the higher its *D* value, the greater is its heat resistance. Heat resistance is also affected by a wide range of other environmental factors, such as pH, water activity and the presence of other solutes, such as sugars and salts.

The extent of microbial inactivation is measured by the number of decimal reductions which can be achieved. This is given by $\log(N_0/N)$, where N_0 is the initial population and N is the final population; and it is determined from the following equation:

$$\log\left(\frac{N_0}{N}\right) = \frac{\text{Heating time}}{D_T} \tag{2.1}$$

There are two important aspects associated with first order reaction kinetics: it is not theoretically possible to achieve 100% reduction and, for a specific heat treatment, the final population increases as the initial population increases.

Example: for an organism with a D_{70} value of 10 s, heating for 10 s at 70 °C will achieve a 90% reduction in the population, 20 s heating will achieve 2*D* (99%), 30 s will achieve 3*D* (99.9%) and 60 s will achieve 6*D* (99.9999%) reduction.

Although it is not theoretically possible to achieve 100% reduction, in practical terms this may appear to be the case. For sterilisation processes, the term *commercial sterility* is used, rather than absolute sterility, to indicate that there will always be a small chance that one or more microorganisms will survive the heat treatment. Increasing the severity of the heating process, e.g. by prolonging the time period or by using higher temperatures, will reduce the chance of finding survivors of any particular bacterium.

Thus, if the initial population had been 10^6 ml^{-1}, after 80 s heating the final population would be 10^{-2} ml^{-1}. It may be difficult to imagine a fraction of an organism, but another way of expressing this is one organism per 100 ml. Thus, if the sample had been packaged in 1-ml portions, it should be possible to find one surviving microorganism in every 100 samples analysed; i.e. 99 would be free of microorganisms. The same heat treatment given to a raw material with a lower count would give one surviving microorganism in every 10 000 ml. Thus if 10 000 (1-ml) samples were analysed, 9999 would be free of viable microorganisms. Note that just one surviving bacterium in a product or package can give rise to a spoiled product or package. In practice, deviations from first order reaction kinetics are often encountered and the reasons for this are discussed in more detail by Gould [4].

For pasteurisation processes the temperature range of interest is 60–90 °C. Sterilisation is a more severe process and temperatures in excess of 100 °C are needed to inactivate heat-resistant spores. Sterilisation processes can be either in a sealed container, 110–125 °C for 10–120 min, or by continuous flow tech-

niques, using temperatures in the range 135–142 °C for several seconds. In both cases, the amount of chemical reaction is increased and the flavour is different to pasteurised milk. The product has a shelf life of up to 6 months at ambient storage conditions.

2.3 Temperature Dependence

As mentioned, most processes do not take place at constant temperature, but involve heating and cooling periods. Therefore, although it is easy to evaluate the effect of the holding period on the heat resistance and the lethality, i.e. the number of decimal reductions of a process, see Eq. (2.1), it is important to appreciate that the heating and cooling may also contribute to the overall lethality. It can easily be demonstrated that reaction rates increase as temperature increases and microbial inactivation is no exception. Food scientists use a parameter known as the z value, to describe temperature dependence. This is based on the observation that, over a limited temperature range, there is a linear relationship between the log of the decimal reduction time and the temperature (see Fig. 2.1).

This is used to define the z value for inactivation of that particular microorganism as follows: the z value is the temperature change which results in a tenfold change in the decimal reduction time. The z value for most heat-resistant spores is about 10 °C, whereas the z value for vegetative bacteria is considerably lower, usually between 4 °C and 8 °C. A low z value implies that the reaction in question is very temperature-sensitive. In general, microbial inactivation is very temperature-sensitive, with inactivation of vegetative bacteria being more temperature-sensitive than heat-resistant spores.

In contrast to microbial inactivation, chemical reaction rates are much less temperature-sensitive than microbial inactivation, having higher z values (20–40 °C; see Table 2.1). This is also the case for many heat-resistant enzymes, although heat-labile enzymes such as alkaline phosphatase or lactoperoxidase are exceptions to this rule. This difference for chemical reactions and microbial inactivation has some important implications for quality improvement when using higher temperatures for shorter times; and this is discussed in more detail in Section 2.5.3.

The relationship between D values at two different temperatures and the z value is given by:

$$\log\left(\frac{D_1}{D_2}\right) = \left[\frac{(\theta_2 - \theta_1)}{z}\right] \tag{2.2}$$

An alternative way of using z values is for comparing processes. For example, if it is known that a temperature of 68 °C is effective for 10 min and the z value is 6 °C; then equally effective processes would also be 62 °C for 100 min or 74 °C for 1 min, i.e. 1 min at θ is equivalent to 0.1 min at $(\theta + z)$ or 10 min at $(\theta - z)$.

Table 2.1 Values of D and z for microbial inactivation, enzyme inactivation and some chemical reactions; from [6] with permission.

Microbe	D_{121} (°C)	z (°C)
Bacillus stearothermophilus NCDO 1096, milk	181.0	9.43
B. stearothermophilus FS 1518, conc. milk	117.0	9.35
B. stearothermophilus FS 1518, milk	324.0	6.7
B. stearothermophilus NCDO 1096, milk	372.0	9.3
B. subtilis 786, milk	20.0	6.66
B. coagulans 604, milk	60.0	5.98
B. cereus, milk	3.8	35.9
Clostridium sporogenes PA 3679, conc. milk	43.0	11.3
C. botulinum NCTC 7272	3.2	36.1
C. botulinum (canning data)	13.0	10.0
Proteases inactivation	0.5–27.0 min at 150 °C	32.5–28.5
Lipases inactivation	0.5–1.7 min at 150 °C	42.0–25.0
Browning	–	28.2; 21.3
Total whey protein denaturation, 130–150 °C	–	30.0
Available lysine	–	30. 1
Thiamin (B_1) loss	–	31.4–29.4
Lactulose formation	–	27.7–21.0

Thus Eq. (2.2) can be rewritten, replacing decimal reduction time (D) by the processing time (t), as:

$$\log\left(\frac{t_1}{t_2}\right) = \left[\frac{(\theta_2 - \theta_1)}{z}\right] \tag{2.3}$$

In the context of milk pasteurisation, if the holder process (63 °C for 30 min) is regarded as being equivalent to the high temperature short time (HTST) process of 72 °C for 15 s, the z value would be about 4.3 °C.

Another approach is to use this concept of equivalence, together with a reference temperature. For example, 72 °C is used for pasteurisation and 121.1 °C and 135 °C for sterilisation processes (see later). Perhaps best known are the standard lethality tables, used in the sterilisation of low-acid foods.

Thus, the lethality at any experimental temperature (T) can be compared to that at the reference temperature (θ), using the following equation:

$$\log L = \frac{(T - \theta)}{z} \tag{2.4}$$

Thus for a standard reference temperature of 121.1 °C and an experimental temperature of 118 °C, using $z = 10$ °C, then $L = 0.49$. Thus, 1 min at 118 °C would be equivalent to 0.49 min at 121.1 °C. Note that a temperature drop of 3 °C will halve the lethality.

Q_{10} is another parameter used to measure temperature dependence. It is defined as the ratio of reaction rate at $T+10$ to that at T, i.e. the increase in reaction rate caused by an increase in temperature of 10 °C. Some D and z values for heat-resistant spores and chemical reactions are given in Table 2.1.

It is interesting that, in spite of the many deviations reported, this log linear relationship still forms the basis for thermal process calculations in the food industry. Gould [4] has surmised that there is a strong view that this relationship remains at least a very close approximation of the true thermal inactivation kinetics of spores. Certainly, the lack of major problems when sterilisation procedures are properly carried out according to the above principles has provided evidence over many years that the basic rationale, however derived, is sound even though it may be cautious.

2.3.1 Batch and Continuous Processing

A process such as pasteurisation can be done batchwise or continuously. Batch processing involves filling the vessel, heating, holding, cooling, emptying the vessel, filling into containers and cleaning the vessel. Holding times may be up to 30 min. An excellent account of batch pasteurisation is provided by Cronshaw [5]. Predicting the heating and cooling times involves unsteady state heat transfer and illustrates the exponential nature of the heat transfer process. The heating time is determined by equating the rate of heat transfer from the heating medium to the rate at which the fluid absorbs energy. Thus:

$$UA(\theta - \theta) = mc\frac{d\theta}{dt} \tag{2.5}$$

which on integration becomes:

$$t = \frac{mc}{UA}\ln\left[\frac{(\theta_h - \theta_l)}{(\theta_h - \theta_f)}\right] \tag{2.6}$$

where m is mass (kg), c is specific heat (J kg^{-1} K^{-1}), A is surface area (m^2), U is OHTC (W m^{-2} K^{-1}) and t is the heating time (s) required to raise the temperature from θ_l (initial temperature) to θ_f (final temperature) using a heating medium temperature, θ_h.

The dimensionless temperature ratio represents the ratio of the initial temperature driving force to the approach temperature. The concept of approach temperature, i.e. how close the product approaches the heating or cooling medium temperature, is widely used in continuous heat exchangers. Heating and cooling times can be long.

Batch processes were easy to operate, flexible, are able to deal with different size batches and different products and this is still the case; also, if well mixed, no distribution of residence times, which is a problem with continuous processes.

Heating and cooling rates are slower and the operation is more labour intensive; it will involve filling, heating, holding, cooling, emptying, cleaning and disinfecting, which may take up to 2 h. Postprocessing contamination (ppc) should be avoided in the subsequent packaging operations.

The alternative process for both pasteurisation and sterilisation involves continuous processes. Some advantages of continuous processes are as follows:

- Foods can be heated and cooled more rapidly compared to in-container processes. This improves the economics of the process and the quality of the product.
- There are none of the pressure constraints which apply to heating products in sealed containers. This allows the use of higher temperatures and shorter times, which results in less damage to the nutrients and improved sensory characteristics, these being: appearance, colour, flavour and texture.
- Continuous processes provide scope for energy savings, whereby the hot fluid is used to heat the incoming fluid. This is known as regeneration and saves both heating and cooling costs (see Section 2.2.3).

Heating processes can be classified as direct or indirect. The most widely used is indirect heating, where the heat transfer fluid and the liquid food are separated by a barrier. For in-container sterilisation, this will be the wall of the bottle and, for continuous processes, the heat exchanger plate or tube wall. In direct processes, steam is the heating medium and the steam comes into direct contact with the product (see Section 2.2.3).

The mechanisms of heat transfer are by conduction in solids and convection in liquids. Thermal conductivity ($W\,m^{-1}\,K^{-1}$) is the property which measures the rate of heat transfer due to conduction. Metals are good conductors of heat, although stainless steel has a much lower value ($\sim 20\ W\,m^{-1}\,K^{-1}$) than both copper ($\sim 400\ W\,m^{-1}\,K^{-1}$) and aluminium ($\sim 220\ W\,m^{-1}\,K^{-1}$). However, it is much higher than glass ($\sim 0.5\ W\,m^{-1}\,K^{-1}$). In general, foods are poor conductors of heat ($\cong 0.5\ W\,m^{-1}\,K^{-1}$) and this can be a problem when heating particulate systems (see Section 2.5.3).

The efficiency of heat transfer by convection is measured by the heat film coefficient. Condensing steam has a much higher heat film coefficient (as well as a high latent heat of vaporisation) than hot water, which is turn is higher than hot air. Inherently, heat transfer by convection is faster than heat transfer by conduction.

In the indirect process, there are three resistances to the transfer of heat from the bulk of a hot fluid to the bulk of a cold fluid, two due to convection and one due to conduction. The overall heat transfer coefficient (U) provides a measure of the efficiency of the heat transfer process and takes into account all three resistances. It can be calculated from:

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} + \frac{L}{k} \tag{2.7}$$

where h_1 and h_2 are the heat film coefficients (W m^{-2} K^{-1}) for the hot fluid and the cold fluid respectively, L is heat exchanger wall thickness (m) and k is the thermal conductivity of the plate or tube wall (W m^{-1} K^{-1}).

The higher the value of U, the more efficient is the heat exchange system. Each one of the terms in Eq. (2.7) represents a resistance. The highest of the individual terms is known as the limiting resistance. This is the one that controls the overall rate of heat transfer. Thus, to improve the performance of a heat exchanger, it is best to focus on the limiting resistance.

The basic design equation for a heat exchanger is as follows:

$$Q = UA\Delta\theta_m \tag{2.8}$$

where Q is the duty or rate of heat transfer (J s^{-1}), $\Delta\theta_m$ (°C or K) is the log mean temperature difference and A is the surface area (m^2).

The duty (Q) is obtained form the following expression:

$$Q = m'c\Delta\theta \tag{2.9}$$

where m' is mass flow rate (kg s^{-1}), c is specific heat capacity (J kg^{-1} K^{-1}) and $\Delta\theta$ is the change in product temperature (K or °C).

In a continuous heat exchanger, the two fluids can either flow in the same direction (co-current) or in opposite directions (counter-current). Counter-current is the preferred direction, as it results in a higher mean temperature driving force and a closer approach temperature.

One of the main practical problems with indirect heating is fouling. This is the formation of deposits on the wall of the heat exchanger. These can introduce one or two additional resistances to heat transfer and lead to a reduction in U. Fouling may be the result of deposits from the food or deposits from the service fluids in the form of sediment from steam, hardness from water or microbial films from cooling water. Fouling may result in a decrease in product temperature and eventually in the product being underprocessed. A further problem is a reduction in the cross-sectional area of the flow passage, which leads to a higher pressure drop. Fouled deposits also need to be removed at the end of the process as they may serve as a breeding ground for bacteria, particularly thermoduric bacteria. For example, for milk, fouling becomes more of a problem as the processing temperature increases and the acidity of the milk increases. Fouling is discussed in more detail by Lewis and Heppell [6]. Heat exchangers also need to be cleaned and disinfected after their use (see Section 2.5.3).

2.3.2
Continuous Heat Exchangers

The viscosity of the product is one major factor which affects the choice of the most appropriate heat exchanger and the selection of pumps. The main types of indirect heat exchanger for fluids such as milk, creams and liquid egg are the

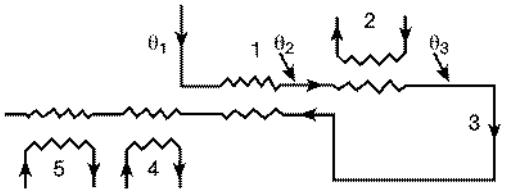


Fig. 2.2 Heat exchanger sections for a high temperature short time (HTST) pasteuriser: 1, regeneration; 2, hot water section; 3, holding tube; 4, mains water cooling; 5, chilled water cooling; from [3] with permission.

plate heat exchanger and the tubular heat exchanger. A high product viscosity gives rise to a high pressure drop, which can cause a problem in the cooling section, especially when phase transitions such as gelation or crystallisation take place. For more viscous products, such as starch-based desserts, a scraped surface heat exchanger may be used (see Section 2.4.3.3).

One of the main advantages of continuous systems over batch systems is that energy can be recovered in terms of regeneration. The layout for a typical regeneration section is shown in Fig. 2.2. The hot fluid (pasteurised or sterilised) can be used to heat the incoming fluid, thereby saving on heating and cooling costs. The regeneration efficiency (RE) is defined as follows:

$$\mathrm{RE} = 100 \times (\text{amount of heat supplied by regeneration/amount of heat required assuming no regeneration}) \quad (2.10)$$

Regeneration efficiencies up to 95% can be obtained, which means that a pasteurised product would be heated up to almost 68 °C by regeneration. Although high regeneration efficiencies result in considerable savings in energy, it necessitates the use of larger surface areas, resulting from the lower temperature driving force and a slightly higher capital cost for the heat exchanger. This also means that the heating and cooling rates are also slower, and the transit times longer, which may affect the quality, especially in UHT processing.

Plate heat exchangers (PHEs; see Fig. 2.3) are widely used both for pasteurisation and sterilisation processes. They have a high OHTC and are generally more compact than tubular heat exchangers. Their main limitation is pressure, with an upper limit of about 2 MPa. The normal gap width between the plates is between 2.5 mm and 5.0 mm, but wider gaps are available for viscous liquids. The narrower the gap, the more pressure required and wide gap plates are not in regular use for UHT treatment of low-acid foods. In general, a PHE is the cheapest option and the one most widely used for low viscosity fluids. However, maintenance costs may be high, as gaskets may need replacing at regular intervals and the integrity of the plates need to be checked at regular intervals, especially those in the regeneration section, where a cracked or leaking plate may allow raw product, e.g. raw milk, to contaminate already pasteurised milk or sterilised milk.

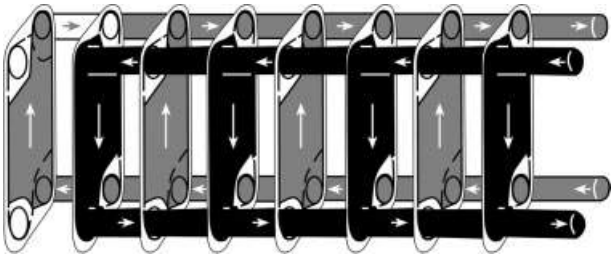


Fig. 2.3 Flow through a plate heat exchanger, by courtesy of APV.

Tubular heat exchangers (see Fig. 2.4) have a lower OHTC than plates and generally occupy a larger space. They have slower heating and cooling rates with a longer transit time through the heat exchanger. In general they have fewer seals and provide a smoother flow passage for the fluid. A variety of tube designs is available to suit different product characteristics. These designs include single tubes with an outer jacket, double or multiple concentric tubes or shell and tube types. Most UHT plants use a multitube design. They can withstand higher pressures than PHEs. Although, they are still susceptible to fouling, high pumping pressures can be used to overcome the flow restrictions. Thus, tubular heat exchangers give longer processing times with viscous materials and with products which are more susceptible to fouling.

For products containing fat, such as milk and cream, homogenisation (see Chapter 15) must be incorporated to prevent fat separation. This may be upstream or downstream. For UHT processes, downstream homogenisation requires the process to be achieved under aseptic conditions and provides an additional risk of recontaminating the product. Upstream homogenisation removes the need to operate aseptically, but is thought to produce a less stable emulsion.

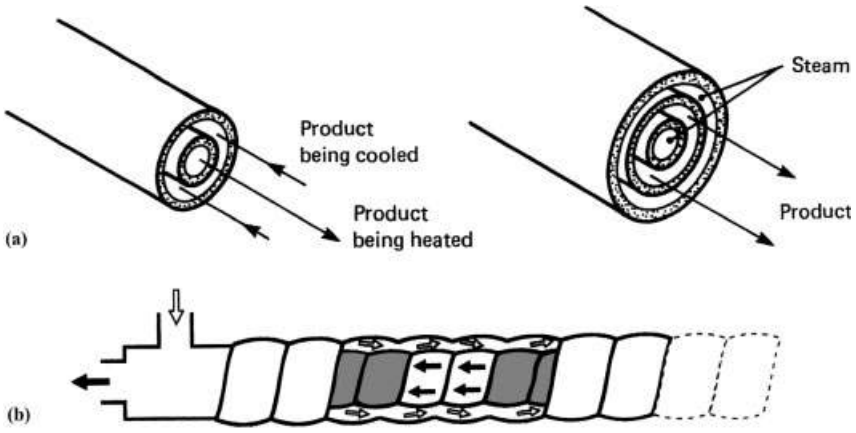


Fig. 2.4 Types of concentric tube heat exchangers: (a) plain wall, (b) corrugated spiral wound; from [7] with permission.

In direct processes, the product is preheated up to a temperature of 75 °C, often by regeneration, before being exposed to culinary steam to achieve a temperature of 140–145 °C. The steam should be free of chemical contaminants and saturated to avoid excessive dilution of the product (which is between about 10% and 15%). This heating process is very rapid. The product is held for a few seconds in a holding tube. Added water is removed by flash cooling, which involves a sudden reduction in pressure to bring the temperature of the product down to between 75 °C and 80 °C. This sudden fall in temperature is accompanied by the removal of some water vapour. There is a direct relationship between the fall in temperature and the amount of water removed. The final temperature and hence the amount of water removed is controlled by the pressure (vacuum) in the flash cooling chamber. This cooling process, like the heating, is very rapid. As well as removing the added water (as vapour), flash cooling removes other volatile components, which, in the case of UHT milk, gives rise to an improvement in the flavour. Direct processes employ a short sharp heating profile and result in less chemical damage, compared to an equivalent indirect process of similar holding time and temperature. They are also less susceptible to fouling and will give long processing times, but their regeneration efficiencies are usually below 50%. Direct processes are usually employed for UHT rather than pasteurisation processes.

There are two principle methods of contacting the steam and the food liquid. Steam can either be injected into the liquid (injection processes) or liquid can be injected into the steam (infusion). There is a school of thought that claims that infusion is less severe than injection since the product has less contact with hot surfaces. However, direct experimental evidence is scant. There is no doubt that direct processes (both injection and infusion) produce a less intense cooked flavour than any indirect process, although claims that direct UHT milk is indistinguishable from pasteurised milk are not always borne out. Successful operation depends upon maintaining a steady vacuum, as the flash cooling vessel operates at the boiling point of the liquid. If the pressure fluctuates, the boiling point also fluctuates; and this leads to boiling over if the pressure suddenly drops, for whatever reason. Thus, maintaining a steady vacuum is a major control point in the operation of these units. Note that some indirect UHT plants may incorporate a de-aeration unit, which operates under the same principle. The effects of heating and cooling profiles will be compared for UHT products in Section 2.4.3.2.

In continuous processes, there is a distribution of residence times. It is important to know whether the flow is streamline or turbulent, as this influences heat transfer rates and the distribution of residence times within the holding tube and also the rest of the plant. This can be established by evaluating the Reynolds number (Re), where:

$$\mathrm{Re} = \frac{\nu D \rho}{\mu} = \frac{4Q\rho}{\Pi \mu D} \tag{2.11}$$

where ν is average fluid velocity (m s^{-1}), ρ is fluid density (kg m^{-3}), D is pipe diameter (m), μ is fluid viscosity (Pas) and Q is volumetric flow rate (m^3 s^{-1}).

Note that the average residence time (based upon the average velocity) can be determined from t_{av} = volume of tube/volumetric flow rate.

For viscous fluids, the flow in the holding tube is likely to be streamline, i.e. its Reynolds Number (Re) is less than 2000 and there is a wide distribution of residence times. For Newtonian fluids, the minimum residence time is half the average residence time. Turbulent flow (Re > 4100) will result in a narrower distribution of residence times, with a minimum residence time of 0.83 times the average residence time. Fig. 2.5 illustrates residence time distributions for three situations, namely plug flow, streamline flow and turbulent flow. Plug flow is

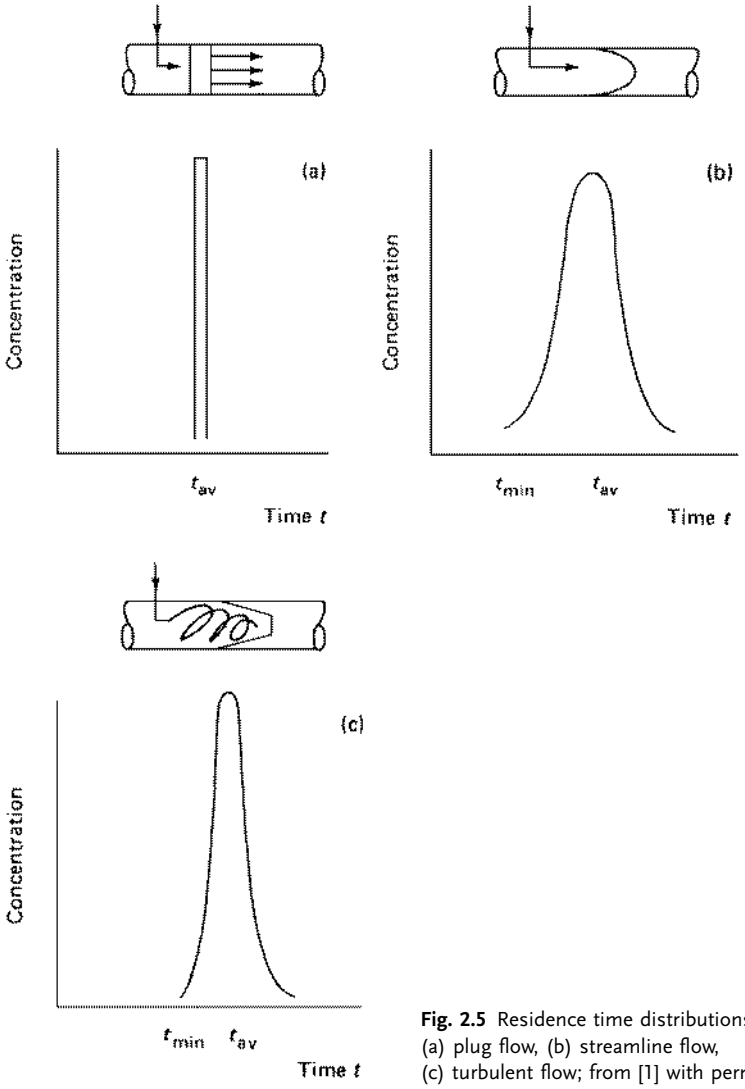


Fig. 2.5 Residence time distributions for: (a) plug flow, (b) streamline flow, (c) turbulent flow; from [1] with permission.

the ideal situation with no spread of residence times, but for both streamline and turbulent flow, the minimum residence time should be greater than the stipulated residence time, to avoid under-processing. Residence time distributions and their implications for UHT processing are discussed in more detail by Lewis and Heppell [6] and Burton [7].

2.4 Heat Processing Methods

The main types of heat treatment will now be covered, namely pasteurisation and sterilisation. A third process is known as thermisation.

2.4.1 Thermisation

Thermisation is a mild process which is designed to increase the keeping quality of raw milk. It is used mainly when it is known that it may not be possible to use raw milk immediately for conversion to other products, such as cheese or milk powder. The aim is to reduce psychrotropic bacteria, which can release heat resistant protease and lipase enzymes into the milk. These enzymes are not inactivated during pasteurisation and may give rise to off flavours if the milk is used for cheese or milk powders. Temperatures used are 58–68 °C for 15 s. Raw milk thus treated can be stored at a maximum of 8 °C for up to 3 days [8]. It is usually followed later by a more severe heat treatment. Thermised milk should show the presence of alkaline phosphatase, to distinguish it from pasteurised milk. To the author's knowledge, there is no equivalent process for other types of foods.

2.4.2 Pasteurisation

Pasteurisation is a mild heat treatment, which is used on a wide range of different types of food products. The two primary aims of pasteurisation are to remove pathogenic bacteria from foods, thereby preventing disease and to remove spoilage (souring) bacteria to improve its keeping quality. It largely stems from the discovery of Pasteur in 1857 that souring in milk could be delayed by heating milk to 122–142 °F (50.0–61.0 °C), although it was not firmly established that the causative agents of spoilage and disease were microorganisms until later in that century. However, even earlier than this, foods were being preserved in sealed containers by a process of sterilisation, so for some considerable time foods were being supplied for public consumption without an understanding of the mechanism of preservation involved. In fact, the first stage in the history of pasteurisation between 1857 and the end of the 19th century might well be called the medical stage, as the main history in heat-treating milk came chiefly from the medical profession interested in infant feeding. By 1895,

it was recognised that a thoroughly satisfactory product can only be secured where a definite quantity of milk is heated for a definite length of time at a definite temperature. By 1927, North and Park [9] had established a wide range of time/temperature conditions for inactivating tubercle bacilli, ranging from 130 °F (54 °C) for 60 min up to 212 °F (100 °C) for 10 s. The effectiveness of heat treatments was determined by taking samples of milk, which had been heavily infected with tubercle organisms and then subjected to different time/temperature combinations, and inoculating the samples into guinea pigs and noting those conditions which did not kill the animals. The use of alkaline phosphatase as an indicator was first investigated in 1933 and is now still standard practice. Pasteurisation is now accepted as the simplest method to counter milk-borne pathogens and has now become commonplace, although there are still some devotees of raw milk. The IDF [10] definition of pasteurisation is as follows: "pasteurisation is a process applied to a product with the objective of minimising possible health hazards arising from pathogenic microorganisms associated with the product (milk) which is consistent with minimal chemical, physical and organoleptic changes in the product". This definition is also applicable to products other than milk, including, creams, icecream mix, eggs, fruit juices, fermented products, soups and other beverages.

Even in the early days of pasteurisation, milk only had a short shelf life, as domestic refrigeration was not widespread. This occurred in the 1940s and had an almost immediate impact on keeping quality. Initially there was also considerable resistance to the introduction of milk pasteurisation, not dissimilar to that now being encountered by irradiation [11]. Pasteurisation does not inactivate all microorganisms: those which survive pasteurisation are termed thermodurics and those which survive a harsher treatment (80–100 °C for 30 min) are termed spore formers. Traditionally it was a batch process – the Holder process – at 63 °C for 30 min, but this was followed by the introduction and acceptance of continuous HTST processes.

2.4.2.1 **HTST Pasteurisation**

HTST processes were investigated in the late 1920s. It was approved for milk in the USA in 1933 and approval for the process was granted in the UK in 1941. Continuous operations offer a number of advantages, such as faster heating and cooling rates, shorter holding times and regeneration, which saves both heating and cooling costs and contributes to the low processing costs incurred in thermal processing operations, compared to many novel techniques. Scales of operations on continuous heat exchangers range between 500 l h^{-1} and 50 000 l h^{-1}, with experimental models down to 50 l h^{-1}. Continuous processing introduces some additional complications which have been well resolved, including flow control, flow diversion and distribution of residence times.

Schematics for the flow of fluid through the heat exchanger and the heat exchange sections are shown in Fig. 2.2 and Fig. 2.6. The fluid first enters the re-

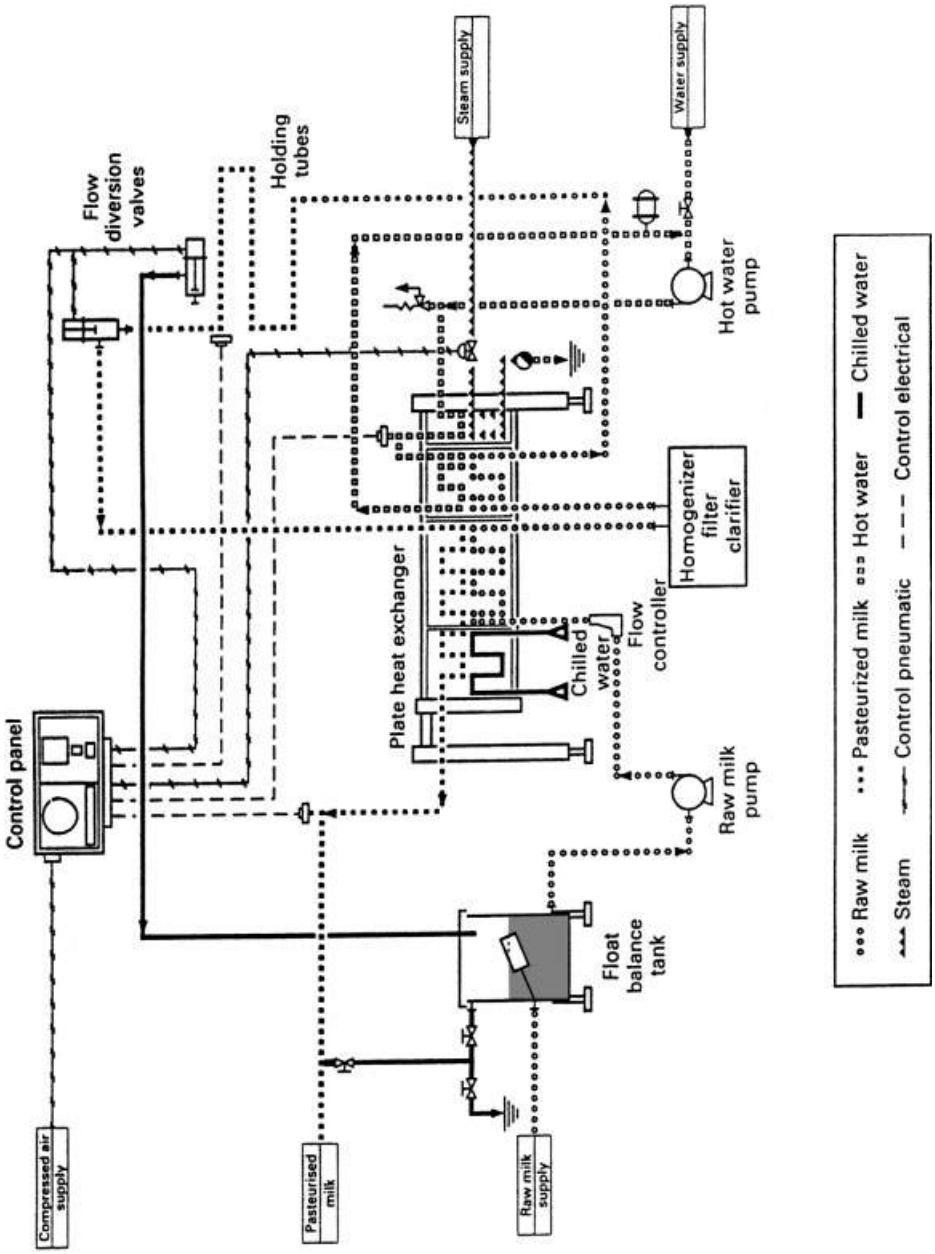


Fig. 2.6 Typical milk pasteurisation system; from [17] with permission.

generation section (A), where it is heated from θ_1 to θ_2 by the fluid leaving the holding tube. It then enters the main heating section, where it is heated to the pasteurisation temperature, θ_3. It then passes through the holding tube. The tube is constructed such that the minimum residence time exceeds the stipulated residence time and this can be determined experimentally at regular intervals. It then passes back into the regeneration section, where it is cooled to θ_4. This is followed by further cooling sections, employing mains water and chilled water. The mains water section is usually dispensed with where it may heat the product rather than cool it, for example at high RE or high mains water temperature. As RE increases, the size and capital cost of the heat exchanger increases; heating rate decreases, which may affect quality, but this is more noticeable in UHT sterilisation [6]. Heating profiles tend to become more linear at high RE efficiencies. Other features are a float-controlled balance tank, to ensure a constant head to the feed pump and a range of screens and filters to remove any suspended debris from the material.

In most pasteurisers, one pump is used. It is crucial that the flow rate remains constant, despite any disturbances in feed composition temperature, or changes in the system characteristics. The two most common options are a centrifugal pump with a flow controller or a positive displacement pump. If the product is to be homogenised, the homogeniser itself is a positive pump and is sized to control the flow rate. In the majority of pasteurisers, the final heating process is provided by a hot water set. Steam is used to maintain the temperature of the hot water at a constant value, somewhere between 2 °C and 10 °C higher than the required pasteurisation temperature. Electrical heating can be used, typically in locations where it would be costly or difficult to install a steam generator (boiler). The holding system is usually a straightforward holding tube, with a temperature probe at the beginning and a flow diversion valve at the end. The position of the temperature probe in the holding tube is one aspect for consideration. When positioned at the beginning, there is more time for the control system to respond to underprocessed fluid, i.e. the time it takes to pass through the tube, but it will not measure the minimum temperature obtained, as there will be a reduction in temperature due to heat loss as the fluid flows through the tube. This could be reduced by insulating the holding tube, but it is not generally considered to be a major problem in commercial pasteurisers.

Ideally temperature control should be within ±0.5 °C. Note that a temperature error of 1 °C, will lead to a reduction of about 25% in the process lethality (calculated for $z=8$ °C). From the holding tube, in normal operation, it goes back into regeneration, followed by final cooling. The pasteurised product may be packaged directly or stored in bulk tanks.

In principle, a safe product should be produced at the end of the holding tube. However, there may be an additional contribution to the total lethality of the process from the initial part of the cooling cycle. Thereafter, it is important to prevent recontamination, both from dirty pipes and from any recontamination with raw feed.

Should this occur, it is known as postpasteurisation contamination; and this can be a major determinant of keeping quality. Failures of pasteurisation pro-

cesses have resulted from both causes. The most serious incidents have caused food poisoning outbreaks and have arisen where pasteurised milk has been recontaminated with raw milk, which must have unfortunately contained pathogens. Such contamination may arise for a number of reasons, all of which involve a small fraction of raw milk not going through the holding tube (see Fig. 2.7). One explanation lies with pinhole leaks or cracks in the plates, which may appear with time, due to corrosion. With plate heat exchangers, the integrity of the plates needs testing. This is most critical in the regeneration section; where there is a possibility of contamination from raw to treated, i.e. from high to low pressure.

An additional safeguard is the incorporation of an extra pump, to ensure that the pressure on the pasteurised side is higher than that on the raw side, but this further complicates the plant. In some countries, this requirement may be incorporated into the heat treatment regulations. Another approach is the use of double-walled plates, which also increases the heat transfer area by about 15–20% due to the air gap. These and other safety aspects have been discussed by Sorensen [13]. Pinholes in the heating and cooling sections could lead to product dilution or product contamination in the hot water or chilled water sections; and this may result in an unexpected microbiological hazards. It is important that plates are regularly pressure-tested and the product tested, by measuring the depression of its freezing point, to ensure that it has not been diluted. Similar problems may arise from leaking valves, either in recycle or detergent lines.

It is now easier to detect whether pasteurised milk has been recontaminated with raw milk, since the introduction of more sensitive instrumentation for detecting phosphatase activity. It is claimed that raw milk contamination as low as 0.01% can be detected. Miller Jones [14] documented a major pasteurisation failure in America, where over 16 000 people were infected with salmonella and ten died. The cause was believed to be due to ppc, caused by a section of the plant which was not easy to drain and clean, hence leading to recontamination of already pasteurised milk.

Some further considerations of the engineering aspects are provided by Kessler [10], SDT [15] and Hasting [16]. Fouling is not considered to be such a problem compared to that found in UHT processing. However, with longer proces-

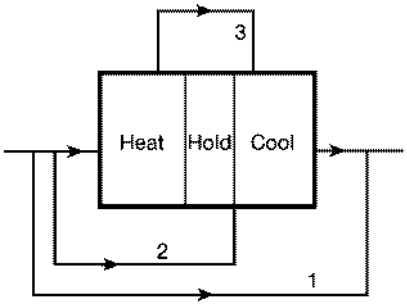


Fig. 2.7 Bypass routes in a commercial pasteuriser: 1, via cleaning routes; 2, via flow diversion route; 3, via regeneration section (e.g. pinhole leak in plates); from [12] with permission.

sing times and poorer quality raw materials, it may have to be accounted for and some products such as eggs may be more prone to fouling. One important aspect is a reduction in residence time due to fouling in the holding tube [16].

The trend is for HTST pasteurisation plants to run for much longer periods (16–20 h), before cleaning and shutdown. Again, monitoring phosphatase activity at regular intervals throughout is useful to ensure uniform pasteurisation throughout and for detecting more subtle changes in plant performance, which may lead to a better estimation of when cleaning is required. However, it has also been suggested that there is an increase in thermophilic bacteria due to an accumulation of such bacteria in the regenerative cooling section arising toward the end of such long processing runs.

Also very important are issues of fouling, cleaning and disinfecting, which are all paramount to the economics of the process.

2.4.2.2 **Tunnel (Spray) Pasteurisers**

Tunnel or spray pasteurisers are widely used in the beverage industry, for continuous heating and cooling of products in sealed containers. They are ideal for high volume throughput. Examples of such products are soft and carbonated drinks, juices, beers and sauces. Using this procedure, ppc should be very much reduced, the major cause being due to defective seams in the containers. There are three main stages in the tunnel, heating, holding and cooling; and in each stage water at the appropriate temperature is sprayed onto the container. Since heating rates are not as high as for plate or tubular heat exchangers, these processes are more suited to longer time/lower temperature processes. The total transit time may be about 1 h, with holding temperatures between 60 °C and 70 °C for about 20 min. Pearse [17] cites 60 °C for 20 min as a proven time/temperature profile. There is some scope for regeneration in these units.

2.4.3 **Sterilisation**

2.4.3.1 **In-Container Processing**

Sterilisation of foods by the application of heat can either be in sealed containers or by continuous flow techniques. Traditionally it is an in-container process, although there have been many developments in container technology since the process was first commercialised at the beginning of the 19th century. Whatever the process, the main concerns are with food safety and quality. The most heat-resistant pathogenic bacterium is *Clostridium botulinum*, which does not grow below pH 4.5. On this basis, the simplest classification is to categorise foods as either as acid foods (pH < 4.5) or low-acid foods (pH > 4.5). Note that a broader classification has been used for canning: low-acid (pH > 5.0), medium-acid (pH 4.5–5.0), acid (pH 4.5–3.7), high-acid (pH < 3.7). However, as mentioned earlier, the main concern is with foods at pH > 4.5. For such foods, the minimum recommended process is to achieve 12*D* reductions for *C. botulinum*. This is

known as the 'minimum botulinum cook'. This requires heating at 121 °C for 3 min, measured at the slowest heating point. The evidence for this producing a safe process for sterilised foods is provided by the millions of units of heat-preserved foods consumed worldwide each year, without any botulinum-related problems.

The temperature of 121.1 °C (250 °F) is taken as a reference temperature for sterilisation processes. This is used in conjunction with the z value for *C. botulinum*, which is taken as 10 °C, to construct standard lethality tables (see Table 2.2). Since lethalities are additive, it is possible to sum the lethalities for a process and determine the total integrated lethal effect, which is known as the *Fo* value.

In mathematical terms, F_0 is defined as the total integrated lethal effect, i.e.:

$$F_0 = \int L dt \tag{2.12}$$

It is expressed in minutes at a reference temperature of 121.1 °C, using the standard lethality tables derived for a z value of 10 °C.

For canned products, it is determined by placing a thermocouple at the slowest heating point in the can and measuring the temperature throughout the sterilisation process. This is known as the general method and is widely used to evaluate the microbiological severity of an in-container sterilisation process. Other methods are available based on knowing the heating and cooling rates of the products.

The F_0 values recommended for a wide range of foods are given in Table 2.3. It can be seen from these values that some foods need well in excess of the minimum botulinum cook, i.e. an *Fo* value of 3 (with values ranging between 4 and 18) to achieve commercial sterility. This is because there are some other bacterial spores which are more heat resistant than *C. botulinum*. The most heat-resistant of these is the thermophile *Bacillus stearothermophilus,* which has a decimal reduction time of about 4 min at 121 °C. Of recent interest is the mesophilic spore-forming bacterium *B. sporothermodurans* [18]. Some heat resistance values for other important spores are summarised by Lewis and Heppell [6] and more detailed compilations are given by Burton [7], Holdsworth [19] and Walstra et al. [20]. Such heat-resistant spores may cause food spoilage, either through the production of acid (souring) or the production of gas. Again, such spores will not grow below pH 4.5 and many of them are inhibited at higher pH values than this: e.g. *B. stearothermophilus*, which causes flat/sour spoilage, will not continue to grow below about pH 5.2.

The severity of the process (*Fo* value) selected for any food depends upon the nature of the spoilage flora associated with the food, the numbers likely to be present in that food and to a limited extent on the size of the container, since more organisms will go into a larger container. Such products are termed commercially sterile, the target spoilage rate being less than 1:10 000. It should be remembered that canning and bottling operations are high-speed operations,

Table 2.2 Lethality values, using a reference temperature of 121.1 °C, z=10 °C. Lethality values are derived from log $L=(T-\theta)/z$, where L=number of minutes at reference temperature equivalent to 1 min at experimental temperature, T=experimental temperature, θ=reference temperature (121.1 °C); from [6] with permission.

Processing temperature		Lethality
(°C)	(°F)	(*L*)
110	230.0	0.078
112	237.2	0.195
114	237.2	0.195
116	240.8	0.309
118	244.4	0.490
120	248.0	0.776
121	249.8	0.977
121.1	250.0	1.000
122	251.6	1.230
123	253.4	1.549
124	255.2	1.950
125	257.0	2.455
126	258.8	3.090
127	260.6	3.890
128	262.4	4.898
129	264.2	6.166
130	266.0	7.762
131	267.8	9.772
132	269.6	12.30
133	271.4	15.49
134	273.2	19.50
135	275.0	24.55
136	276.8	30.90
137	278.6	38.90
138	280.4	48.98
139	282.2	61.66
140	284.0	77.62
141	285.8	97.72
142	287.6	123.0
143	289.4	154.9
144	291.2	195.0
145	293.0	245.5
146	294.8	309.2
147	296.6	389.0
148	298.4	489.8
149	300.2	616.6
150	302.0	776.24

Table 2.3 F_o values which have been successfully used for products on the UK market, from [23] with permission.

Product	Can size(s)	F_o values
Baby foods	Baby food	3–5
Beans in tomato sauce	All	4–6
Peas in brine	Up to A2	6
	A2 to A10	6–8
Carrots	All	3–4
Green beans in brine	Up to A2	4–6
	A2 to A10	6–8
Celery	A2	3–4
Mushrooms in brine	A 1	8–10
Mushrooms in butter	Up to A1	6–8
Meats in gravy	All	12–15
Sliced meat in gravy	Ovals	10
Meat pies	Tapered, flat	10
Sausages in fat	Up to 1 lb	4–6
Frankfurters in brine	Up to 16Z	3–4
Curries, meats and vegetables	Up to 16Z	8–12
Poultry and game, whole in brine	A2.5 to A10	15–18
Chicken fillets in jelly	Up to 16 oz	6–10
'Sterile' ham	1 lb, 2 lb	3–4
Herrings in tomato	Ovals	6–8
Meat soups	Up to 16Z	10
Tomato soup, not cream of	All	3
Cream soups	A1 to 16Z	4–5
	Up to A10	6–10
Milk puddings	Up to 16Z	4–10
Cream	4 oz to 6 oz	3–4

with the production of up to 50 000 containers every hour from one single product line. It is essential that each of those containers is treated exactly the same and that products treated on every subsequent day are also subjected to the same conditions.

The philosophy for ensuring safety and quality in thermal processing is to identify the operations where hazards may occur (critical control points) and devise procedures for controlling these operations to minimise the hazards (see Chapter 10). Of crucial importance is the control of all those factors which affect heat penetration into the product and minimise the number of heat-resistant spores entering the can prior to sealing. It is also important to ensure that the closure (seal) is airtight, thereby eliminating ppc.

Since it is not practicable to measure the temperatures in every can, the philosophy for quality assurance involves verifying that the conditions used throughout the canning process lead to the production of a product which is commercially sterile and ensuring that these conditions are reproduced on a daily basis.

Processing conditions such as temperature and time are critical control points. Others are raw material quality (especially counts of heat-resistant spores), and controlling all factors affecting heat penetration. These include filling temperature, size of headspace, ratio of solids to liquid, liquid viscosity, venting procedures and reducing ppc by seal integrity, cooling water chlorination and avoiding the handling of wet cans (after processing) and drying them quickly. It is also important to avoid large pressure differentials between the inside and outside of a container. Drying cans quickly after cooling and reducing manual han-

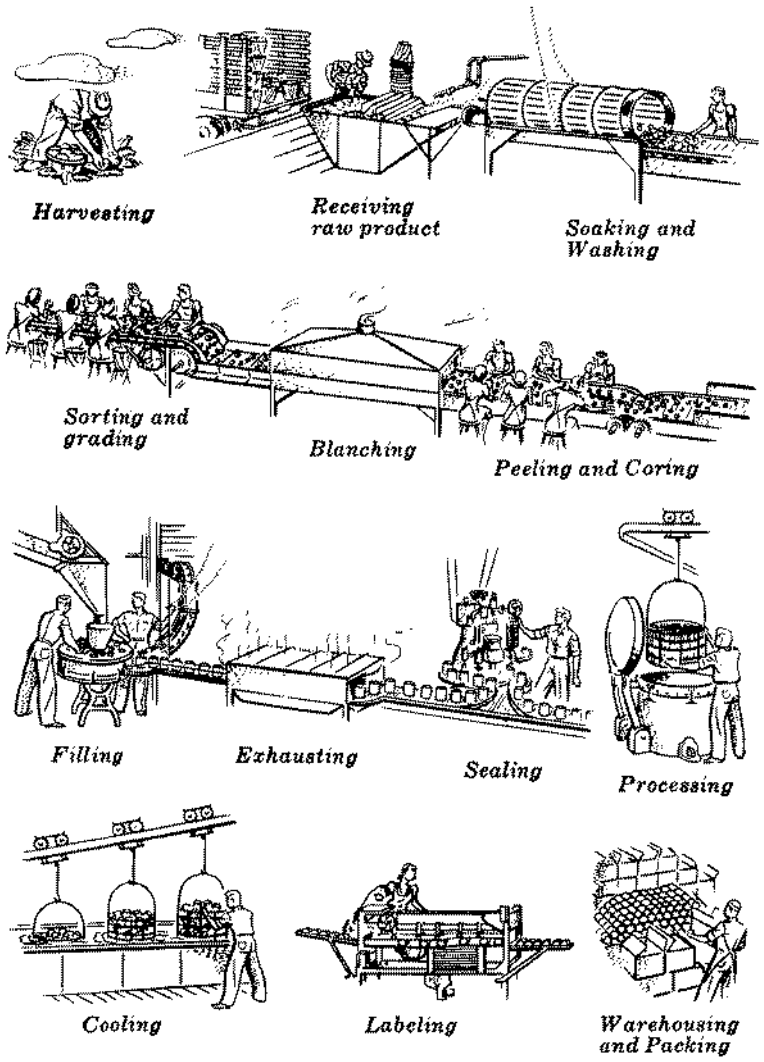


Fig. 2.8 The canning process; from [21] with permission.

dling of cans are very important for minimising ppc. In-container sterilisation involves the integration of a number of operations, all of which will contribute to the overall effectiveness of the process. These are summarised both in Fig. 2.8 and by Jackson and Shinn [21] and will be further discussed below.

Types of Container For in-container processes, there is now a wide range of containers available. The most common container is the can and its lid. There have been many developments since its inception as mild steel coated with tin plate: these include soldered or welded cans, two- and three-piece cans, tinfree steel and aluminium and there are many different lacquers to prevent chemical interactions between the metal and the foods (see Chapter 9). These modifications have been made to effect cost reductions and provide greater convenience. Cans are able to tolerate reasonable pressure differentials. Glass bottles and jars are common. Sterilised milk was traditionally produced in glass bottles but products in glass need to be heated and cooled more slowly to avoid breakage of the containers. Other containers used for in-container sterilisation include flexible pouches, plastic trays and bottles. All these materials have different wall thicknesses, different thermal conductivities and different surface area to volume ratios, all of which can influence heat transfer rates and thus the quality of the final heat-treated product.

Supply of Raw Materials It is essential that there is a supply of raw materials of the right quality and quantity: the requirements for contracts between the supplier and the food processor which protect both their interests. For fruit and vegetables, appropriate varieties should be selected for canning, as they must be able to withstand the heat treatment without undue softening or disintegration. Also important are their sensory characteristics, spore counts and chemical contaminants. Food to be processed should be transported quickly to the processing factory.

Preliminary Operations Preliminary operations depend upon the type of food and could include inspection, preparation, cleaning, peeling, destoning and size reduction. Where it is used, water quality is important and there will be considerable waste for disposal. Note that some preprepared vegetables may have been sulphited (see Chapter 1) and for sterilisation in metal cans these should be avoided, as sulphite may strip tinplate (see Chapter 9).

Blanching is an important operation, using hot water or steam (see Chapter 1). Different products have different time/temperature combinations. Blanching inactivates enzymes and removes intracellular air, thereby helping to minimise the internal pressure generated on heating. It also increases the density of food and softens cell tissue, which facilitates filling and it further cleans the product as well as removing vegetative organisms. It may lead to some thermal degradation of nutrients and some leaching losses for hot water blanching. An excellent detailed review on blanching is given by Selman [22].

Filling is an important operation, both for the product and any brine syrup or sauce that may accompany it. It is important to achieve the correct filled and

drained weights and headspace. When using hot filling, the filling temperature must be controlled, as variations will lead to variations in the severity of the overall sterilisation process.

Sauces, brines and syrups may be used; and their composition may be covered by Codes of Practice. One of the main reasons for their use is to improve heat transfer.

Exhausting is another important process. It involves the removal of air prior to sealing, helping to prevent excessive pressure development in the container during heat treatment, which would increase the likelihood of damaging the seal. Four methods are available for exhausting: mechanical vacuum, thermal exhausting, hot filling and steam flow closing.

The next process is **sealing**, i.e. producing an airtight (hermetic) seal. For cans, this is achieved by a double rolling process (see Chapter 9) and the integrity of the seal is checked by visual inspection and by tearing down the seal and looking at the overlap and tightness. Can seamers can handle from 50 to 2000 cans per minute.

Containers are **sterilised** in retorts, which are large pressure vessels. Batch and continuous retorts are available and the heating medium is either steam, pressurised hot water, or steam/air mixtures. Some examples are shown in Figs. 2.9, 2.10. For steam, there is a fixed relationship between its pressure and temperature, given by steam tables, Lewis [1] and Holdsworth [19].

There should be an accurate system for recording temperatures and an indicating thermometer. A steam pressure gauge should be incorporated, as this will act indirectly as a second device for monitoring temperature. Discrepancies between temperature and pressure readings could suggest some air in the steam or that the instruments are incorrect [6]. Venting involves the removal of air from the retort and venting conditions need to be established for each individual retort. Every product will have its own unique processing time and temperature; and these would have been established to ensure that the appropriate F_0 value is achieved for that product. Ensuring $12D$ reductions for *C. botulinum* (safety) does ensure that a food is safe but more stringent conditions may be required for commercial sterility. The processing time starts when the temperature in the retort reaches the required processing temperature.

Cooling is a very important operation and containers should be cooled as quickly as possible down to a final temperature of 35–40 °C. As the product cools, the pressure inside the can falls and it is important to ensure that the pressure in the retort falls at about the same rate. This is achieved by using a combination of cooling water and compressed air to avoid a sudden fall in pressure caused by steam condensation. Water quality is important and it should be free of pathogenic bacteria. This can be assured by chlorination, but an excessive amount should be avoided as this may cause container corrosion. It is also important to avoid too much manual handling of wet cans to reduce the levels of ppc.

The containers are then labelled and stored. A small proportion may be incubated at elevated temperatures to observe for blown containers.

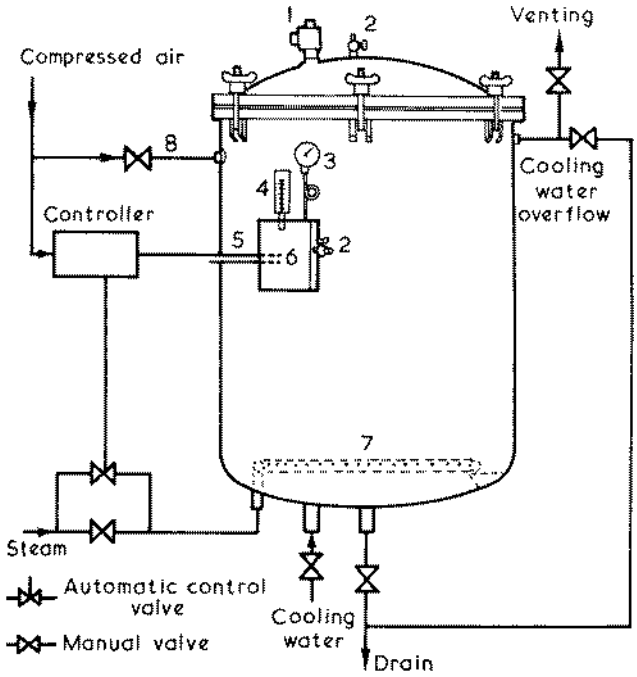


Fig. 2.9 A vertical batch retort equipped for cooling under air pressure: 1, safety valve; 2, valve to maintain a steam bleed from retort during processing; 3, pressure gauge; 4, thermometer; 5, sensing element for contoller; 6, thermometer box; 7, steam spreader; 8, air inlet for pressure cooling; from [23] with permission of the authors.

Quality Assurance Strict monitoring of all these processes is necessary to ensure that in-container sterilisation provides food which is commercially sterile. A summary of the requirements are as follows.

The target spoilage rate is <1 in 10^4 containers. There should be strict control of raw material quality, control of all factors affecting heat penetration and final product assessment (filled and drained weights, sensory characteristics and regular seal evaluation). Use should be made of hazard analysis critical control points (HACCP) and advice given in 'Food and drink – good manufacturing practice' [24].

One of the main problems with in-container processing is that there is considerable heat damage to the nutrients and changes in the sensory characteristics, which can be assessed by the cooking value [19], where a reference temperature of 100 °C is used with a z value of 20–40 °C (typically about 33 °C). Also summarised [19] are the z values for the sensory characteristics, which range between 25 °C and 47 °C. Further information on canned food technology is provided by the following excellent reference works: Stumbo [25], Hersom and Hul-

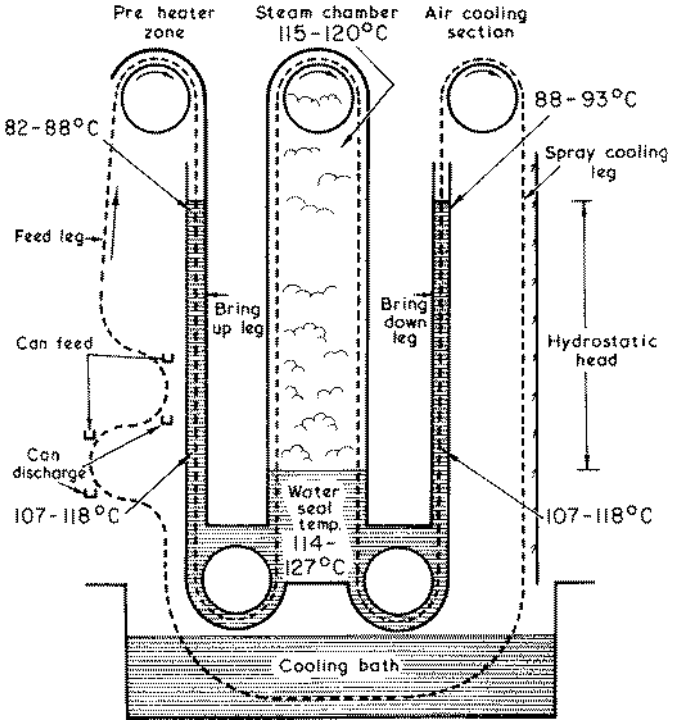


Fig. 2.10 Diagram showing the principle of the hydrostatic steriliser; from [23] with permission of the authors.

land [26], Jackson and Shinn [21], Rees and Bettison [27], Footitt and Lewis [28] and Holdsworth [19].

It is noteworthy that most fruit and other acidic products, e.g. pickles and fermented products, need a less harsh heat treatment; and processing conditions of 100 °C for 10–20 min are usually applied.

2.4.3.2 **UHT Processing**

More recently, continuous sterilisation processes have been introduced. Ultra-high temperature (UHT) or aseptic processing involves the production of a commercially sterile product by pumping the product through a heat exchanger. To ensure a long shelf life, the sterile product is packed into presterilised containers in a sterile environment (see Chapter 9). An airtight seal is formed, which prevents reinfection, in order to provide a shelf life of at least 3 months at ambient temperature. It has also been known for a long time that the use of higher temperatures for shorter times results in less chemical damage to important nutrients and functional ingredients within foods, thereby leading to an improvement in product quality [7].

Sterilisation of the product is achieved by rapid heating to temperatures about 140 °C and holding for several seconds, followed by rapid cooling. Ideally, heating and cooling should be as quick as possible. Indirect and direct heating methods are available (see Section 2.3). UHT products are in a good position to be able to improve the quality image of heat processed, ambient stable foods.

Safety and Spoilage Considerations From a safety standpoint, the primary objective is the production of commercially sterile products, with an extended shelf life. The main concern is inactivation of the most heat resistant pathogenic spore, namely *C. botulinum*. The safety criteria used for UHT processing should be based upon those well established for canned and bottled products. The minimum *Fo* value for any low acid food should be 3. Fruit juices and other acidic products require a less stringent process or may be heat-treated in their containers, in either tunnels or oventype equipment.

The time/temperature conditions required to achieve the minimum botulinum cook can be estimated at UHT temperatures. At a temperature of 141 °C, a time of 1.8 s would be required. There is experimental evidence to show that the data for botulinum can be extended up to 140 °C [29]. For UHT products, an approximate value of *Fo* can be obtained from the holding temperature (*T*, °C) and minimum residence time (*t*, s): Eq. (2.13). In practice, the real value is higher than this estimated value because of the lethality contributions from the end of the heating period and the beginning of the cooling period as well as some additional lethality from the distribution of residence times.

$$Fo = 10^{\frac{(T-121.1)}{10}} \cdot \frac{t}{60} \tag{2.13}$$

Therefore, the botulinum cook should be a minimum requirement for all low acid foods, even those where botulinum has not been a problem, e.g. for most dairy products. In the UK, there are statutory heat treatment regulations for some UHT products:

- milk, 135 °C for 1 s
- cream, 140 °C for 2 s
- milkbased products, 140 °C for 2 s
- icecream mix, 148.9 °C for 2 s.

In some cases, lower temperatures and longer times can be used, provided it can be demonstrated that the process renders the product free from viable microorganisms and their spores. If no guidelines are given, recommended *Fo* values for similar canned products would be an appropriate starting point (typically 6–10 for dairy products). Sufficient pressure must also be applied in order to achieve the required temperature. A working pressure in the holding tube in excess of 100 kPa over the saturated vapour pressure, corresponding to the UHT temperature, has been suggested.

UHT processes, like canned products, are also susceptible to ppc. This does not usually give rise to a public health problem, although contamination with patho-

gens cannot be ruled out. However, high levels of spoiled product do not improve its quality image, particularly if not detected before it is released for sale. Contamination may arise from the product being reinfected in the cooling section of the plant, or in the pipelines leading to the aseptic holding/buffer tank or the aseptic fillers. This is avoided by heating all points downstream of the holding tube at 130 °C for 30 min. The packaging material may have defects, or the seals may not be airtight, or the packaging may be damaged during subsequent handling All these could result in an increase in spoilage rate (see Section 2.5).

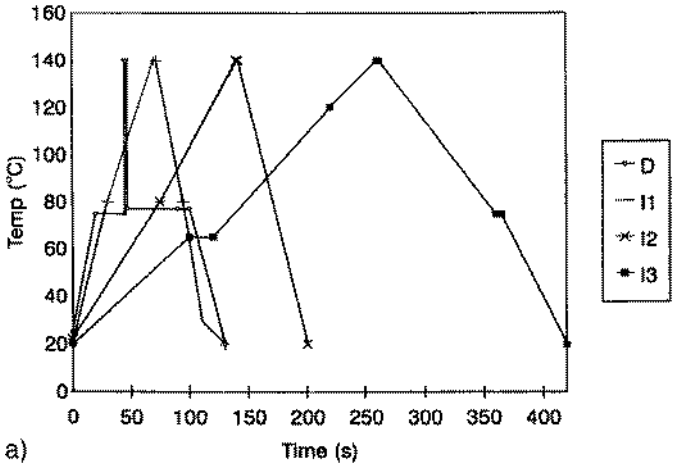
Process Characterisation: Safety and Quality Aspects As in other thermal processes, the requirements for safety and quality are in conflict, as a certain amount of chemical change will occur during adequate sterilisation of the food. Therefore, it is important to ask what is meant by quality and what is the scope for improving the quality. One aspect of quality, which has already been discussed, is reducing microbial spoilage. A second important aspect is minimising chemical damage and reducing nutrient loss. In this aspect, UHT processing offers some distinct advantages over in-container sterilisation. Chemical reactions are less temperature-sensitive, so the use of higher temperatures, combined with more rapid heating and cooling help to reduce the amount of chemical reaction. This has been well documented by Kessler [31, 32] and more recently by Browning et al. [33]. For example, reactions such as colour changes, hydroxymethyl furfural formation, thiamine loss, whey protein denaturation and lactulose formation will all be higher for in-container sterilisation compared to UHT processing.

There is also a choice of indirect heat exchangers available, such as plates, tubular and scraped surface, as well as direct steam injection or infusion plants, all of which will heat products at different rates and shear conditions. To better understand the quality of products produced from a UHT process, knowledge of the temperature/time profile for the product is required. Some examples of such profiles are shown for a number of different UHT process plants are shown in Fig. 2.11. There are considerable differences in the heating and cooling rates for indirect processes and between the direct and indirect processes due to steam injection and flash cooling. Because of these differences similar products processed on different plants may well be different in quality. A more detailed discussion is given by Burton [7].

Two other parameters introduced for UHT processing of dairy products, but which could be more widely used for other UHT products, are B^* and C^* values [31]. The reference temperature used (135 °C) is much closer to UHT processing temperatures, than that used for Fo (121 °C) or cooking value (100 °C) estimations.

B^* is a microbial parameter used to measure the total integrated lethal effect of a process. A process giving $B^*=1$ would be sufficient to produce nine decimal reductions of mesophilic spores and would be equivalent to 10.1 s at 135 °C.

C^* is a parameter to measure the amount of chemical damage taking place during the process. A process giving $C^*=1$ would cause 3% destruction of thiamine and would be equivalent to 30.5 s at 135 °C.



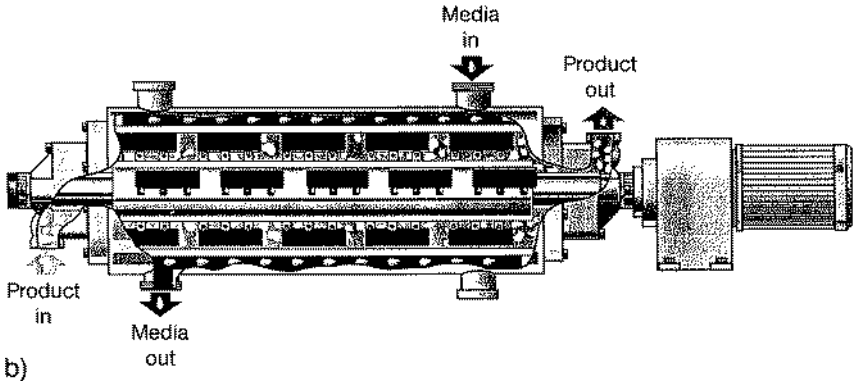


Fig. 2.11 (a) Temperature/time profiles for different UHT plants; from [6] with permission. (b) Cutaway view of a horizontal scraped surface heat exchanger; by courtesy of APV.

Again the criterion in most cases is to obtain a high B* and a low C* value.

Calculations of B^* and C^* based on the minimum holding time (t, s) and temperature (T, °C) are straightforward:

$$B^* = 10^{\frac{(T-135.0)}{10.5}} \cdot \frac{t}{10.1} \tag{2.14}$$

$$\text{and } C^* = 10^{\frac{(T-135.0)}{31.4}} \cdot \frac{t}{30.5} \tag{2.15}$$

Browning et al. [33] evaluated a standard temperature/holding time combination of 140 °C for 2 s for heating at cooling times from 1 s to 120 s.

It is noticeable that the amount of chemical change increased significantly as the heating and cooling times increased and that the longer heating and cooling

times gave rise to quite severe microbiological processing conditions, i.e. high *B** and *Fo* values. At a heating period of about 8 s, the amount of chemical damage done during heating and cooling exceeds that in the holding tube. It is this considerable increase in chemical damage which is more noticeable in terms of decreasing the quality of the product. However this may be beneficial in those circumstances where a greater extent of chemical damage may be required; i.e. for inactivating enzymes or for heat-inactivation of natural toxic components, e.g. trypsin inhibitor in beans or softening of vegetable tissue (cooking). Differences in temperature/time processes arise due to use of different heat exchangers and the extent of energy savings by regeneration.

Chemical damage could be further reduced by using temperatures in excess of 145 °C. The best solution would be the direct process, with its accompanying rapid heating and cooling. Steam is mixed with the product, preheated to about 75 °C, by injection or infusion. The steam condenses and becomes an ingredient in the product. Steam utilisation is between about 10–15% (mass/mass). There are special requirements for the removal of impurities from the steam, such as water droplets, oil and rust. Heating is almost instantaneous. The condensed steam is removed by flash cooling, if required. It will also remove heat-induced volatile components, e.g. hydrogen sulphide and other low molecular weight compounds containing sulphur which are thought to be responsible for the initial cooked flavour in milk. There is also a reduction in the level of dissolved oxygen, which may improve the storage stability of the product. Advantages of this process are reduced chemical damage and a less intense cooked flavour for many products. One problem would be the very short holding times required and the control of such short holding times. In theory, it should be possible to obtain products with very high *B** and low *C** values, at holding times of about 1 s. For indirect processes, the use of higher temperatures may be limited by fouling considerations and it is important to ensure that the heat stability of the formulation is optimised. It may be worthwhile developing simple tests to assess heat stability. The alcohol stability test is one such test which is useful for milk products. Generally, direct systems give longer processing runs than indirect processes.

Raw Material Quality and Other Processing Conditions In terms of controlling the process, the following aspects will also merit some attention. Aspects of raw material quality relate to an understanding of the physical properties of the food, through to spore loadings and chemical composition. Of particular concern would be high levels of heat-resistant spores and enzymes in the raw materials, as these could lead to increased spoilage and stability problems during storage; dried products such as milk other dairy powders, cocoa, other functional powders, and spices are examples to be particularly careful with. Quality assurance programmes must ensure that such poor quality raw materials are avoided. The product formulation is also important; the nature of the principle ingredients; the levels of sugar, starch, salt as well as the pH of the mixture, particularly if there is appreciable amounts of protein. Some thought should be

given to water quality, particularly the mineral content. Reproducibility in metering and weighing ingredients is also important, as is ensuring that powdered materials are properly dissolved or dispersed and that there are no clumps, which may protect heat resistant spores. Homogenisation conditions may be important. Is it necessary to homogenise and if so at what pressures? Should the homogeniser be positioned upstream or downstream of the holding tube? Will two-stage homogenisation offer any advantages? Homogenisation upstream offers the advantage of breaking down any particulate matter to facilitate heat transfer, as well as avoiding the need to keep the homogeniser sterile during processing. All of these aspects will influence both the safety and the quality of the products.

It is important to ensure that sterilisation and cleaning procedures have been properly accomplished. The plant should be sterilised downstream of the holding tube at 130 °C for 30 min. Cleaning should be adequate (detergent concentrations and temperatures) to remove accumulated deposits and the extent of fouling should be monitored, if possible. Steam barriers should be incorporated if some parts of the equipment are to be maintained sterile, whilst other parts are being cleaned.

All the important experimental parameters should be recorded. This will help ensure that any peculiarities can be properly investigated. Regular inspection and maintenance of equipment are important, particularly eliminating leaks. All staff involved with the process should be educated in order to understand the principles and be encouraged to be diligent and observant. With experience, further hazards will become apparent and methods for controlling them introduced. The overall aim should be to further reduce spoilage rates and to improve the quality of the product.

It is recognised that UHT processing is more complex than conventional thermal processing [24]. The philosophy of UHT processing should be based upon preventing and reducing microbial spoilage by understanding and controlling the process. One way of achieving this by using the principles of Hazard analysis critical control points (HACCP [34], also see Chapter 10). The hazards of the process are identified and procedures adapted to control them. An acceptable initial target spoilage rate of less than one in 10^4 should be aimed for. Such low spoilage rates require very large numbers of samples to be taken to verify that the process is being performed and controlled at the desired level. Initially a new process should be verified by 100% sampling. Once it is established that the process is under control, sampling frequency can be reduced and sampling plans can be designed to detect any spasmodic failures. More success will result from targeting high risk occurrences, such as start up, shut down and product changeovers. Holding time and temperature are perhaps the two most critical parameters. Recording thermometers should be checked and calibrated regularly, and accurate flow control is crucial (as for pasteurisation).

2.4.3.3 Special Problems with Viscous and Particulate Products

Continuous heat processing of viscous and particulate products provides some special problems. For viscous products it may be possible to use a tubular heat exchanger, but it is more probable that a scraped surface heat exchanger will be required. Fig. 2.11 b shows a typical scraped surface heat exchanger. This incorporates a scraper blade which continually sweeps product away from the heat transfer surface. These heat exchangers are mechanically more complex, with seals at the inlet and outlet ends of the scraper blade shaft. Overall heat transfer coefficients are low, the flow is streamline with a consequent increase in the spread of residence times and the fluid being heated may also be nonNewtonian. Heating and cooling rates are fairly slow and the process is generally more expensive to run, because of the higher capital and maintenance costs and less scope for regeneration. They may be used for pasteurisation or sterilisation processes. Two specialist uses of this equipment are for freezing icecream and for margarine and lowfat spread manufacture. In most cases, increasing the agitation speed improves heat transfer efficiency by increasing the overall heat transfer coefficient. However, when cooling products, some may become very viscous, e.g. due to product crystallisation; and higher agitation speeds may create additional frictional heat, making the product warmer rather than cooling. This is known as viscous dissipation. Scraped surface heat exchangers can also handle particulate systems, up to 25 mm diameter.

Problems arise with particulate systems because the solid phase conducts heat slowly so it will take longer to sterilise the particles compared to the liquid. Also, determination of the heat film coefficient is difficult due to the uncertainty in the relative velocity of the solid with respect to the liquid. There can also be problems determining the residence time distribution of the solid particles.

One special system is Ohmic heating, whereby particulate material is pumped through a nonconducting tube in which electrodes are placed. An electric current is passed through the material and the heating effect is caused by resistive heating and is determined by the electrical conductivity of the food as well as the applied voltage. If the solid particles are the same conductivity as the liquid, there should be no difference in heating rates between them. Unfortunately there is no rapid cooling process to accompany it and little scope for energy regeneration.

A second approach is to have a selective holding tube system, whereby larger particles are held up in the holding tube for a longer period of time. A third approach involves heating the solid and liquid phases separately and recombining them. This is the feature of the Jupiter heating system. These systems are discussed in more detail by Lewis and Heppell [6].

Dielectric heating, particularly microwaves, may also be used for pasteurisation and sterilisation of foods in continuous processes. For foods containing solid particles, there are some advantages in terms of being able to generate heat within the particles. Factors affecting the rate of heating include the field strength and frequency of the microwave energy and the dielectric loss factor of

the food. However, dielectric heating processes are much more complex compared to well established HTST and UHT processes and the benefits that might result have to be weighed against the increased costs. One major drawback is that of non-uniform heating. This is a critical aspect in pasteurisation and sterilisation processes, where it is a requirement that all elements of the food reach a minimum temperature for a minimum time; for example 70 °C for 2 min to inactivate *E. coli* 0157. If part of the food only reaches 65 °C, even though other parts may well be above 70 °C, serious underprocessing will occur. Identifying with greater certainty where the slower heating points are will help to improve matters. Brody [35] provides further reading on microwave food pasteurisation.

2.5 Filling Procedures

For pasteurisation and extended shelf-life products, clean filling systems are used and for UHT products aseptic systems are required. There are a number of aseptic packaging systems available. They all involve putting a sterile product into a sterile container in an aseptic environment. Pack sizes range from individual portions (14 ml) and retail packs (125 ml to 1 l), through to bag in the box systems up to 1000 l. The sterilising agent is usually hydrogen peroxide (35% at about 75–80 °C), the contact time is short and the residual hydrogen peroxide is decomposed using hot air. The aim is to achieve a 4*D* process for spores. Superheated steam has been used for sterilisation of cans in the Dole process. Irradiation may be used for plastic bags (see Chapter 9).

Since aseptic packaging systems are complex, there is considerable scope for packaging faults to occur, which leads to spoiled products. Where faults occur, the spoilage microorganisms are random and could include those microorganisms which would be expected to be inactivated by UHT processing; and these often result in blown packages.

Packages should be inspected regularly to ensure that they are airtight, again focusing upon those more critical parts of the process, e.g. startup, shutdown, product changeovers and, for carton systems, reel splices and paper splices. Sterilisation procedures should be verified. The seal integrity of the package should be monitored as well as the overall microbial quality of packaging material itself. Care should be taken to minimise damage during subsequent handling. All these could result in an increase in spoilage rate.

2.6 Storage

UHT products are commonly stored at room (ambient) temperature and good quality products should be microbiologically stable. Nevertheless, chemical reactions and physical changes can take place which will change the quality of the

product. Particularly relevant are oxidation reactions and Maillard browning, both of which can lead to a deterioration in the sensory characteristics of the product. These are discussed in more detail by Burton [7] and Lewis and Heppell [6].

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