# D. Heat processing by direct and radiated energy

# 18

# Dielectric, ohmic and infrared heating

Dielectric (microwave and radio frequency) energy and infrared (or radiant) energy are two forms of electromagnetic energy (Fig. 18.1). They are both transmitted as waves, which penetrate food and are then absorbed and converted to heat. In contrast, ohmic (or resistance) heating uses the electrical resistance of foods to directly convert electricity to heat.

Foods can be heated by either direct or indirect methods: dielectric and ohmic heating are direct methods in which heat is generated within the product, whereas infrared heating is an indirect method that relies on heat that is generated externally being applied to the surface of the food mostly by radiation, but also by convection and to a lesser extent, conduction.

The main differences between dielectric, ohmic and infrared energy can be summarised as follows:

- Dielectric energy induces molecular friction in water molecules to produce heat, whereas ohmic heating is due to the electrical resistance of a food and infrared energy is simply absorbed and converted to heat.
- Dielectric heating is determined in part by the moisture content of the food, whereas the extent of heating by radiant energy depends on the surface characteristics and colour of the food and ohmic heating depends on the electrical resistance of the food.
- Dielectric and ohmic heating are used to preserve foods, whereas infrared radiation is mostly used to alter the eating qualities by changing the surface colour, flavour and aroma.
- Commercially, microwaves and radio frequency energy are produced at specified frequency bands that are allocated to prevent interference with radio transmissions, whereas radiant heat is less controlled and has a wider range of frequencies. Ohmic heating uses mains frequency electricity.
- The depth of penetration into a food is directly related to frequency; the lower frequency dielectric energy penetrates more deeply than radiant energy. In contrast, ohmic heating penetrates throughout the food instantly.
- The thermal conductivity of the food (Chapter 1) is a limiting factor in infrared heating, whereas it is not so important in dielectric and ohmic heating.

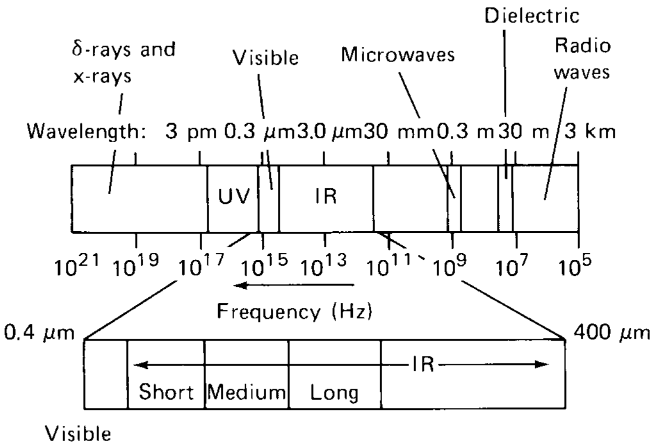


**Fig. 18.1** Electromagnetic spectrum.
(Courtesy of the Electricity Council.)

## 18.1 Dielectric heating

### 18.1.1 Theory

The majority of foods contain a substantial proportion of water. The molecular structure of water consists of a negatively charged oxygen atom, separated from positively charged hydrogen atoms and this forms an electric dipole. When a microwave or radio frequency electric field is applied to a food, dipoles in the water and in some ionic components such as salt, attempt to orient themselves to the field (in a similar way to a compass in a magnetic field). Since the rapidly oscillating electric field changes from positive to negative and back again several million times per second, the dipoles attempt to follow and these rapid reversals create frictional heat. The increase in temperature of water molecules heats surrounding components of the food by conduction and/or convection. Because of their widespread domestic use, some popular notions have arisen that microwaves ‘heat from the inside out’. What in fact occurs is that outer parts receive the same energy as inner parts, but the surface loses its heat faster to the surroundings by evaporative cooling. It is the distribution of water and salt within a food that has the major effect on the amount of heating (although differences also occur in the rate of heating as a result of the shape of the food, at its edges etc.).

The depth of penetration of both microwaves and radio frequency energy is determined by the dielectric constant and the loss factor of the food. These properties have been recorded for some foods (Kent, 1987), (Table 18.1). They vary with the moisture content and temperature of the food and the frequency of the electric field. In general, the lower the loss factor (i.e. greater transparency to microwaves) and the lower the frequency, the greater the penetration depth. It is possible to choose a frequency from the permitted bands that will give a suitable electric field strength for a given loss factor. Because most foods have a high moisture content and therefore a high loss factor, they readily absorb microwave and radio frequency energy and flash-over is not a problem. However, care is needed when selecting equipment for drying low moisture foods (Section 18.1.3) to prevent the electric field strength from exceeding a level at which flash-over would take place. Radio frequency energy is mostly used to heat or evaporate

**Table 18.1** Dielectric properties of materials at 20–25ºC and 2450 MHz

| Material | Dielectric constant ($F\,m^{-1}$) | Loss factor | Penetration depth (cm) |
|---|---|---|---|
| Banana (raw) | 62 | 17 | 0.93 |
| Beef (raw) | 51 | 16 | 0.87 |
| Bread | 4 | 0.005 | 1170 |
| Brine (5%) | 67 | 71 | 0.25 |
| Butter | 3 | 0.1 | 30.5 |
| Carrot (cooked) | 71 | 18 | 0.93 |
| Cooking oil | 2.6 | 0.2 | 19.5 |
| Distilled water | 77 | 9.2 | 1.7 |
| Fish (cooked) | 46.5 | 12 | 1.1 |
| Glass | 6 | 0.1 | 40 |
| Ham | 85 | 67 | 0.3 |
| Ice | 3.2 | 0.003 | 1162 |
| Paper | 4 | 0.1 | 50 |
| Polyester tray | 4 | 0.02 | 195 |
| Potato (raw) | 62 | 16.7 | 0.93 |

Adapted from Mudget (1982), Buffler (1993) and Mohsenin (1984).

moisture from a product, whereas higher frequency microwaves are used for defrosting and low pressure drying (Jones, 1987). Garcia and Bueno (1998) describe improved energy efficiency from combined microwave and hot air drying.

***Microwaves***

The depth of penetration of microwaves is found from the loss factor and the frequency of the microwaves:

$$x = \frac{\lambda_0}{2\pi\sqrt{(\epsilon' \tan\delta)}} \qquad \boxed{18.1}$$

where $x$ (m) = the depth of penetration; $\lambda$ (m) = the wavelength, $\epsilon'$ = dielectric constant and $\tan\delta(\epsilon''/\epsilon')$ = loss tangent (or loss factor or dissipation constant).

The power absorbed by the food is found using:

$$P = 55.61 + 10^{-14} f E^2 \epsilon'' \qquad \boxed{18.2}$$

where $P$ ($W\,m^{-3}$) = power per unit volume, $f$ (Hz) = frequency and $E$ ($V\,m^{-1}$) = electrical field strength.

Microwave penetration increases dramatically when water changes phase to ice (Fig. 18.2), possibly because the molecules are less free to move or absorb energy from the

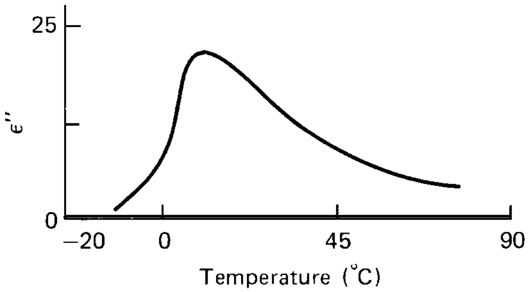


**Fig. 18.2** Variation in dielectric loss factor of water and ice. (After Lewis (1990).)

alternating electric field. Ice therefore has a lower loss factor than water and this has important implications for microwave thawing and tempering applications (Section 18.1.3). Glass, papers and some polymer films have a low loss factor and are not therefore heated. Metals reflect microwaves and are not heated (Chapter 24), therefore making microwave ovens very efficient in energy use as the metal oven is not heated.

***Radio frequency heating***

This operates using a similar principle to microwave heating, but at lower frequencies (Fig. 18.1). Food is passed between electrodes and a radio frequency voltage is applied across the electrodes. This changes the orientation of water dipoles in a similar way to microwaves and results in very rapid heating. Radio frequency heating allows greater concentration of heat energy, selectivity in the location of heating and accuracy in control of the duration of heating. However, the thickness of the food is restricted by the distance between the capacitor plates, which is an important limitation of the method.

A simple method to calculate the amount of radio frequency energy needed for a particular process is

$$E = \frac{m(\theta_1 - \theta_2)C_p}{863} \qquad \boxed{18.3}$$

where $E$ = energy supplied (kW), $m$ = mass flow rate of product (kg h$^{-1}$), $\theta_1$ = final product temperature (ºC), $\theta_2$ = initial product temperature (ºC), $C_p$ = specific heat (kJ$^{-1}$ kg$^{-1}$K$^{-1}$) (courtesy of Strayfield International).

There are a number of additions to the calculated amount of energy required:

- 1 kW is added for each 1.4 kg of water to be evaporated per hour in a drying application.
- An additional 10–20% of energy required is added to account for surface cooling, depending on the surface area to volume ratio of the product.
- If it is assumed that the equipment is 65% efficient in the use of energy supplied, an additional correction is needed to calculate the actual power requirement.

In drying applications for baked goods, radio frequency ovens heat the product to a point at which rapid evaporation of water can take place and then supply the latent heat of evaporation (Chapter 15). If the product is to be dried to around 4% moisture, this is usually 'free' moisture which is easily removed at 100ºC. However, for lower final moisture contents, it is necessary to remove moisture that is 'bound' into the cellular structure of the food, and higher temperatures are needed (see Section 1.5). Typically a temperature of 102–105ºC is needed to achieve 3% moisture, 105–110ºC for 2% moisture and 116ºC for 1.5% moisture. When products are reduced to these very low moisture levels, there are likely to be changes to the colour of baked goods that are similar to those found in conventional ovens. The advantages of microwave and radio frequency heating can be summarised as:

- heating is rapid
- the surface of the food does not overheat, which produces minimum heat damage and no surface browning
- equipment is small, compact, clean in operation and suited to automatic control
- there is no contamination of foods by products of combustion.

### 18.1.2 Equipment

Microwave equipment consists of a microwave generator (termed a *magnetron*) (Fig. 18.3), aluminium tubes named *wave guides*, and a metal chamber for batch operation, or a tunnel fitted with a conveyor belt for continuous operation. Because microwaves heat all biological tissues, there is a risk of leaking radiation causing injury to operators, particularly to eyes which have insufficient blood flow to provide sufficient cooling. Chambers and tunnels are therefore sealed to prevent the escape of microwaves. Detailed descriptions of component parts and operation of microwave heaters are given by Copson (1975) and Buffler (1993).

The magnetron is a cylindrical diode ('di' meaning two and 'electrode'), which consists of a sealed copper tube with a vacuum inside. The tube contains copper plates pointing towards the centre like spokes on a wheel. This assembly is termed the 'anode' and has a spiral wire filament (the cathode) at the centre (Fig. 18.3). When a high voltage (e.g. 4000 V) is applied, the cathode produces free electrons, which give up their energy to produce rapidly oscillating microwaves, which are then directed to the waveguide by electromagnets. The waveguide reflects the electric field internally and thus transfers it to the heating chamber. It is important that the electric field is evenly distributed inside the heating chamber to enable uniform heating of the food. In batch equipment a rotating antenna or fan is used to distribute the energy, or the food may be rotated on a turntable. Both methods reduce shadowing (areas of food which are not exposed to the microwaves). In continuous tunnels a different design of antennae is used to direct a beam of energy over the food as it passes on a conveyor. It is important that the power output from the magnetron is matched to the size of the heating chamber to prevent flash-over. Power outputs of continuous industrial equipment range from 30 to 120 kW.

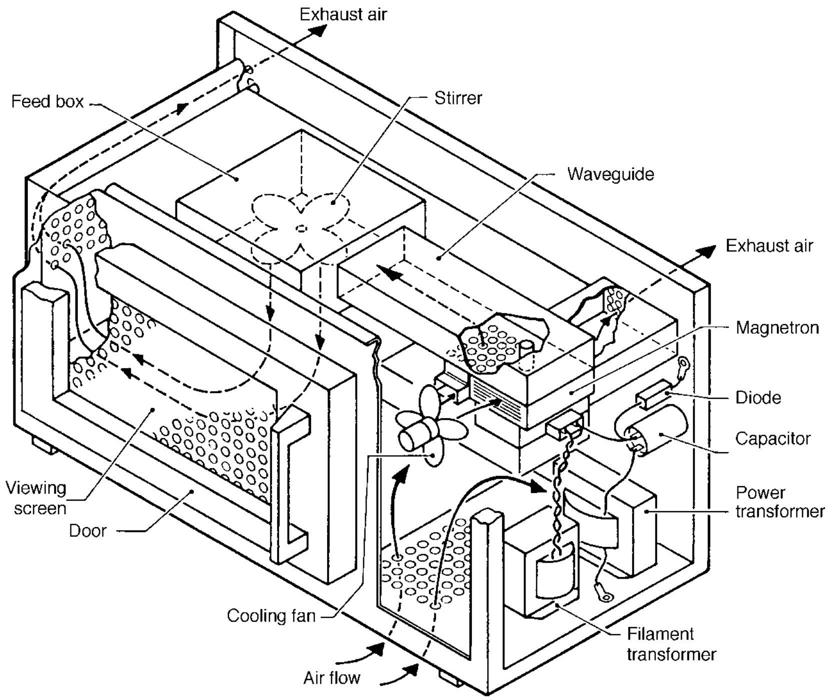


**Figure 18.3** A microwave oven showing the magnetron.
(From Buffler (1993).)

Radio frequency heaters consist of banks of capacitor plates, most often located at the end of bakery tunnel ovens (Chapter 16) or conveyor driers (Chapter 15) with the conveyor band passing between the plates. The electrical circuit is arranged so that the food becomes an essential electrical component. Variations in the amount of food passing between the plates, its temperature and moisture content, will therefore cause a variation in the power output of the generator. This is a valuable self controlling feature: for example, the loss factor of a food falls as the moisture content is reduced and the power output correspondingly falls, so reducing the possibility of burning the food.

### 18.1.3 Applications

The high rates of heating and absence of surface changes to the food have led to studies of dielectric heating of a large number of foods. The most important industrial applications are thawing, tempering, dehydration and baking. These are reviewed by Rosenberg and Bogl (1987a) and Decareau (1985, 1990). Other applications, which involve bulk heating of foods with higher moisture contents (for example blanching and pasteurisation), are less successful. This is due to the low depth of penetration in large pieces of food and to evaporative cooling at the surface, which results in survival of large numbers of micro-organisms. These applications are discussed briefly in this section and are reviewed by Rosenberg and Bogl (1987b). Accelerated freeze drying by microwaves has been extensively investigated (Copson, 1975), but the process remains expensive and is not widely used commercially (Chapter 22).

***Thawing and tempering***

During conventional thawing of frozen foods (Chapter 21), the lower thermal conductivity of water, compared with ice, reduces the rate of heat transfer and thawing slows as the outer layer of water increases in thickness. Microwaves and radio frequency energy are used to rapidly thaw small portions of food and for melting fats (for example butter, chocolate and fondant cream) (Jones, 1987). However, difficulties arise with larger (e.g. 25 kg) frozen blocks (for example egg, meat, fish and fruit juice) used in industrial processes. Water has a higher loss factor than ice and, as a result, heats rapidly once the ice melts. In the large blocks, thawing does not take place uniformly, and some portions of the food may cook while others remain frozen. This is overcome to some extent by reducing the power and extending the thawing period or by using pulsed microwaves to allow time for temperature equilibration.

A more common application is '*tempering*' frozen foods. Here the temperature is raised from around −20ºC to −3ºC and the food remains firm but is no longer hard. After frozen food has been tempered, it is more easily sliced, diced or separated into pieces. Tempering is widely used for meat and fish products, which are more easily boned or ground at a temperature just below the freezing point, and for butter and other edible fats. If foods are tempered but not allowed to melt, the lower energy cost gives a good return on investment in dielectric equipment. The energy required to temper frozen beef, for example, is 62.8 J/g from −17.7 to −4.4ºC whereas 123.3 J/g is needed to raise the temperature a further 2.2ºC as more rapid melting begins to occur (Decareau, 1990). Production rates range from 14 t of meat per hour or 1.5–6 t of butter per hour in equipment which has power outputs of 25–150 kW. The advantages over conventional tempering in cold rooms include:

- faster processing (for example meat blocks are defrosted in 10 min instead of several days in a cold room)

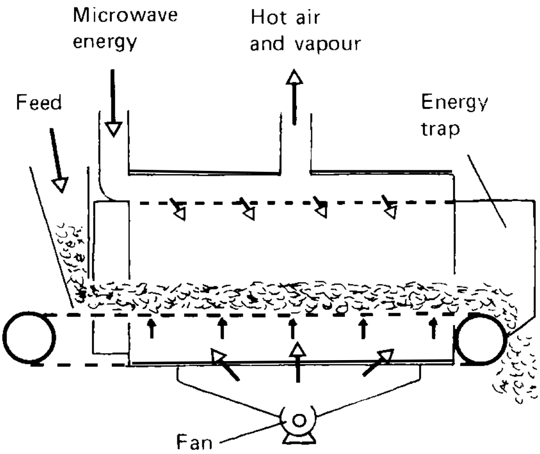


**Fig. 18.4** Continuous microwave finish drying equipment. (After Decareau (1985).)

- there is a minimal amount of food being processed at any one time and little loss or spoilage in the event of a process delay
- greater flexibility in operation
- the cost of operating a refrigerated tempering room is eliminated
- no drip loss or contamination, which improves product yields and reduces nutritional losses
- improved plant productivity and simplified production scheduling
- savings in storage space and labour
- more hygienic defrosting because products are defrosted in the storage boxes
- better control over defrosting conditions and hence improved product quality.

***Dehydration***

The main disadvantages of hot-air drying are:

- low rates of heat transfer, caused by the low thermal conductivity of dry foods (Chapter 1, Table 1.5)
- damage to sensory characteristics and nutritional properties caused by long drying times and overheating at the surface
- oxidation of pigments and vitamins by hot air
- case hardening (Chapter 15).

Microwaves and radio frequency energy overcome the barrier to heat transfer caused by the low thermal conductivity. This prevents damage to the surface, improves moisture transfer during the later stages of drying and eliminates case hardening. The radiation selectively heats moist areas while leaving dry areas unaffected. It is not necessary to heat large volumes of air, and oxidation by atmospheric oxygen is minimised. However, the higher cost of microwaves and radio frequency units, together with the smaller scale of operation, compared with traditional methods of dehydration, restrict microwave drying to 'finishing' (removing the final moisture) of partly dried or low-moisture foods (Fig. 18.4).

For example, in pasta drying the fresh pasta is pre-dried in hot air to 18% moisture and then in a combined hot air and microwave drier to lower the moisture content to 13%. Drying times are reduced from 8 h to 90 min, bacterial counts are 15 times lower, there is a reduction in energy consumption of 20–25%, the drying tunnel is reduced from 36–48 m to 8 m, clean-up time is reduced from 24 to 6 person-hours and there is no case hardening (Decareau, 1985, 1990). In grain finish drying, microwaves are cheaper, more energy efficient and quieter than conventional methods and do not cause dust pollution. The lower drying temperature also improves grain germination rates.

In conventional freeze drying, the low rate of heat transfer to the sublimation front limits the rate of drying (Chapter 22). Microwave freeze drying overcomes this problem because heat is supplied directly to the ice front. However, careful control over drying conditions is necessary to prevent localised melting of the ice. Any water produced in the drying food heats rapidly, owing to the higher loss factor, and causes a chain reaction, leading to widespread melting and an end to sublimation.

### *Baking*

The efficiency of baking is improved by radio frequency or microwave finishing, for thin products such as breakfast cereals, babyfoods, biscuits, crackers, crispbread and sponge cake. Conventional ovens operate effectively when products have relatively high moisture contents, but the thermal conductivity falls as baking proceeds, and considerable time is necessary to bake the centre of the product adequately without excessive changes to the surface colour. Radio frequency or microwave heaters are located at the exit to tunnel ovens (Chapter 16) to reduce the moisture content and to complete the baking without further changes in colour. This reduces baking times by up to 30% and hence increases the throughput of the ovens. Meat pies, which require a good crust colour in addition to pasteurisation of the filling, can be baked in about one third of the time required in a conventional oven by the use of radio frequency heating (Jones, 1987). Other advantages include:

- increases in production by up to 50%
- savings in energy, space and labour costs
- close control of final moisture contents (typically ± 2%) and automatic levelling of moisture contents as only moist areas are heated
- separate control over baking and drying stages allows separate contro1 over internal and external product colour and moisture content
- improved product texture and elimination of ‘centre bone’ (dense dough in the centre of cookies)
- improved taste as flavours are subjected to shorter periods at high temperatures.

### *Other applications*

Compared with conventional cooking, microwave *rendering* of fats improves the colour, reduces fines by 95% and costs by 30% and does not cause unpleasant odours (Decareau, 1985). Microwave *frying* is not successful when deep baths of oil are used, but can be used with shallow trays in which the food is heated rapidly (Chapter 17). There is also less deterioration in oil quality (Copson, 1975). Doughnuts are cooked without oil using microwaves, which reduces processing times by 20% and increases product yield by 25% (Schiffman *et al.*, 1972). Other commercial microwave cooking applications include bacon and meat patties for the fast-food industry and investigation of skinless frankfurters and other sausage products by setting meat emulsions in microwave transparent moulds (Decareau, 1990).

*Blanching* by microwaves has been extensively investigated, but at present the higher costs, compared with steam blanching (Chapter 10), have prevented its use for relatively low-value vegetables. Microwave blanching of products that are more difficult to blanch by conventional methods is under development but may be limited by the high capital investment. Studies of combined steam and microwave blanching are reported to reduce blanching time (Huxsoll *et al.*, 1970).

*Pasteurisation* of packed complete pasta meals, soft bakery goods and peeled potatoes by microwaves is reported by Brody (1992). Most systems developed so far involve packaging the products in flat packages using thermoform/vacuum/gas flush seal equipment (Chapters 20 and 25). Packages are heated in tunnel conveyors, up to 25 m long, using a combination of microwaves and hot air at 70–90ºC, followed by an equilibration stage where the slowest heating parts of the packs reach 80–85ºC within 10 min. The packs are then cooled to 1–2ºC and have a shelf life of approximately 40 days at 8ºC. Details of a procedure for the microwave pasteurisation of fruit juices, to inactivate pectinesterase, are reported by Copson (1975) and for fruits in syrup by Brody (1992).

*Sterilisation* by microwaves is achieved in laminated pouches made from polypropylene/EVOH or PVDC/polypropylene (Chapter 24) in the Multitherm process. The pouches, which are transparent to microwaves, are formed and filled from a continuous reel of film but are not separated. This produces a chain of pouches that passes through a continuous hydrostat system, similar to a small hydrostatic steam steriliser (Chapter 12). In this case the pouches are submerged in a medium that has a higher dielectric constant than the product and heating is by microwaves instead of steam. In a system described by Stenstrom (1972, 1973), the product passes through seven liquid baths, heated at up to 90ºC, and the final sterilising temperature reaches more than 130ºC, before cooling. Both sterilisation and pasteurisation using microwaves have yet to be widely used in the food industry, but they have the potential to become increasingly important.

### 18.1.4 Effect on foods

Microwaves and radio frequency energy have no direct effect on micro-organisms, in contrast with ionising radiation (Chapter 8), and all changes are caused by heat alone. In pasteurisation and blanching applications, the high rates of heat transfer for a specified level of microbial or enzyme destruction result in reduced losses of heat-sensitive nutrients (for example there is no loss of carotene in microwave-blanched carrots, compared with 28% loss by steam blanching and 45% loss by water blanching (von Loesecke, 1942)). However, the results for some foods are highly variable and, for these, microwave heating offers no nutritional advantage over steaming. Changes to foods in other types of processing (frying, baking dehydration, etc.) are described in the relevant chapters. The effects of microwave cooking on nutrient retention in domestic and catering applications are described by Klein (1982) and Lachance (1975).

## 18.2 Ohmic heating

Also termed ‘resistance heating’ or ‘electroheating’, this is a more recent development in which an alternating electric current is passed through a food, and the electrical resistance of the food causes the power to be translated directly into heat. As the food is an electrical component of the heater, it is essential that its electrical properties (its resistance) are matched to the capacity of the heater.

The concept of direct heating in this way is not new, but it has been developed into a commercial process during the last 15 years by the APV Baker company, using a licensed design by EA Technology. The process can be used for UHT sterilisation of foods, and especially those that contain large particles (up to 2.5 cm) that are difficult to sterilise by other means (see Chapter 12). It is now in commercial use in Europe, the USA and Japan for:

- aseptic processing of high added-value ready meals, stored at ambient temperature
- pasteurisation of particulate foods for hot filling
- pre-heating products before canning
- high added-value prepared meals, distributed at chill temperatures (Fryer, 1995).

Ohmic heating is more efficient than microwave heating because nearly all of the energy enters the food as heat. Another important difference is that microwave and radio frequency heating have a finite depth of penetration into a food whereas ohmic heating has no such limitation. However, microwave heating requires no contact with the food, whereas ohmic heating requires electrodes to be in good contact. In practice the food should be liquid or have sufficient liquid with particulate foods to allow good contact and to pump the product through the heater.

The advantages of ohmic heating are as follows:

- the food is heated rapidly ($1°C\,s^{-1}$) at the same rate throughout and the absence of temperature gradients results in even heating of solids and liquids if their resistances are the same
- heat transfer coefficients do not limit the rate of heating
- temperatures sufficient for UHT processing can be achieved
- there are no hot surfaces for heat transfer, as in conventional heating, and therefore no risk of surface fouling or burning of the product which results in reduced frequency of cleaning
- heat sensitive foods or food components are not damaged by localised over-heating
- liquids containing particles can be processed and are not subject to shearing forces that are found in, for example, scraped surface heat exchangers (Chapter 12)
- it is suitable for viscous liquids because heating is uniform and does not have the problems associated with poor convection in these materials
- energy conversion efficiencies are very high (>90%)
- lower capital cost than microwave heating
- suitable for continuous processing.

Further details are given by Sastry (1994) and Rahman (1999).

### 18.2.1 Theory

Foods that contain water and ionic salts are capable of conducting electricity but they also have a resistance which generates heat when an electric current is passed through them. The electrical resistance of a food is the most important factor in determining how quickly it will heat. Conductivity measurements are therefore made in product formulation, process control and quality assurance for all foods that are heated electrically. Electrical resistance of a food is measured using a multimeter connected to a conductivity cell. The measured resistance is converted to conductivity using:

$$\sigma = (1/R)(L/A) \qquad \boxed{18.4}$$

**Table 18.2** Electrical conductivity of selected foods at 19ºC

| Food | Electrical conductivity ($S\,m^{-1}$) |
|---|---|
| 1 Potato | 0.037 |
| 2 Carrot | 0.041 |
| 3 Pea | 0.17 |
| 4 Beef | 0.42 |
| 5 Starch solution (5.5%) | |
| (a) with 0.2% salt | 0.34 |
| (b) with 0.55% salt | 1.3 |
| (c) with 2% salt | 4.3 |

From Kim *et al.* (1996).

where $\sigma$ ($S\,m^{-1}$) = product conductivity, $R$ (ohms) = measured resistance, $L$ (m) = length of the cell and $A$ ($m^2$) = area of the cell.

In composite foods, the conductivity of the particle is measured by difference (i.e. the product conductivity minus the carrier medium conductivity). Data on electrical conductivity of foods (Table 18.2) is as yet relatively scarce, but has a much greater range than thermal conductivity (Chapter 1, Table 1.5). It can vary from $10^8\,S\,m^{-1}$ for copper to $10^{-8}\,S\,m^{-1}$ for an insulating material such as wood. Electrical conductivity is also expressed as the inverse: *specific electrical resistance*. Unlike metals, where resistance increases with temperature, the electrical resistance of a food falls by a factor of 2 to 3 over a temperature rise of 120ºC (Reznick, 1996). It can also vary in different directions (e.g. parallel to, or across, a cellular structure), and can change if the structure changes (e.g. gelatinisation of starch, cell rupture or air removal after blanching).

It can be seen in Table 18.2 that the conductivity of vegetables is lower than for muscle tissue, and this in turn is considerably lower than for a sauce or gravy. The salt content of a gravy is typically 0.6–1% and from the data (5b) in Table 18.2 the conductivity of the beef is about a third of that of the gravy. This has important implications for UHT processing of particles (Section 18.2.2): if in a two-component food, consisting of a liquid and particles, the particles have a lower electrical resistance, they are heated at a higher rate. This is not possible in conventional heating due to the lower thermal conductivity of solid foods, which slows heat penetration to the centre of the pieces (Chapter 1), (Fig. 18.5). Ohmic heating can therefore be used to heat sterilise particulate foods under UHT conditions without causing heat damage to the liquid carrier or over-cooking of the outside of particles. Furthermore, the lack of agitation in the heater maintains the integrity of particles and it is possible to process large particles (up to 2.5 cm) that would be damaged in conventional equipment.

The most important feature of ohmic heating is the rate of heat generation, which in addition to the electrical resistance of the product, depends on the specific heat capacities of each component, the way that food flows through the equipment and its residence time in the heater. If the two components have similar resistances, the lower moisture (solid portion) heats faster than the carrier liquid. However, the calculation of heat transfer is extremely complex, involving the simultaneous solution of equations for electrical, thermal and fluid flow fields and is beyond the scope of this book. Details are given in Fryer (1995) and Sastry and Li (1996). A simplified theory of heating is given below.

The resistance in an ohmic heater depends on the specific resistance of the product, and the geometry of the heater:

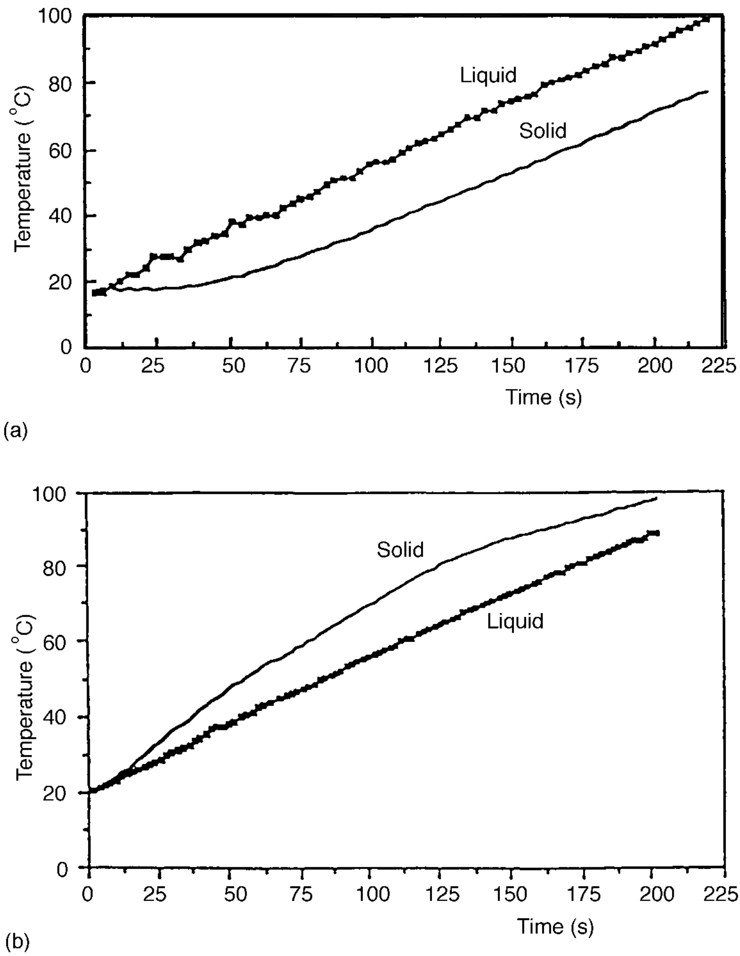


**Fig. 18.5** Heat penetration into solid pieces of food by (a) conventional heating and (b) ohmic heating.
(Adapted from Fryer (1995).)

$$R = (R_s x)/A \qquad \boxed{18.5}$$

where $R$ (ohms) = total resistance of the heater, $R_s$ (ohms $m^{-1}$) = specific resistance of the product, $x$ (m) = distance between the electrodes and $A$ ($m^2$) = area of the electrodes.

The resistance determines the current that is generated in the product:

$$R = \frac{V}{I} \qquad \boxed{18.6}$$

where $V$ (volts) = voltage applied and $I$ (amps) = current.

The available 3-phase power sources in most countries have 220–240 volts per phase at a frequency of 50 Hz and to make the best use of the power, the geometry of the heater and the resistance of the product have to be carefully matched. If the resistance is too high, the current will be too low at maximum voltage. Conversely, if the resistance is too low, the maximum limiting current will be reached at a low voltage and again the heating power will be too low.

Every product has a critical current density and if this is exceeded, there is likely to be arcing (or flash-over) in the heater. The current density is found by:

$$I_d = I/A \qquad \boxed{18.7}$$

where $I_d$ (amps cm$^{-2}$) = current density.

The minimum area for the electrodes can therefore be calculated once the limiting current density and maximum available current are known. As resistance is determined in part by the area of the electrodes (equation 18.5), the distance between the electrodes can be calculated. It is important to recognise that the design of the heater is tailored to products that have similar specific electrical resistances and it cannot be used for other products without modification.

The rate of heating is found using equation (18.8):

$$Q = m.C_p.\Delta\theta \qquad \boxed{18.8}$$

and the power by

$$P = V\,I \qquad \boxed{18.9}$$

and

$$P = R\,I^2 \qquad \boxed{18.10}$$

Assuming that heat losses are negligible, the temperature rise in a heater is calculated using

$$\Delta\theta = \frac{V^2 \sigma_a A}{x m c_p} \qquad \boxed{18.11}$$

where $\Delta\theta$ (°C) = temperature rise, $\sigma_a$ (S m$^{-1}$) = average product conductivity throughout temperature rise, $A$ (m$^2$) = tube cross-sectional area, $x$ (m) = distance between electrodes, $M$ (kg s$^{-1}$) = mass flowrate and $c_p$ (J kg$^{-1}$ °C$^{-1}$) = specific heat capacity of the product.

### 18.2.2 Equipment and applications

As described in Section 18.2.1, the design of ohmic heaters must include the electrical properties of the specific product to be heated, because the product itself is an electrical component. This concept is only found elsewhere in radio frequency heating and requires more specific design considerations than those needed when choosing other types of heat exchangers. Ohmic heaters should therefore be tailored to a specific application and the following factors taken into account:

- the type of product (electrical resistance and change in resistance over the expected temperature rise)
- flowrate
- temperature rise (determines the power requirement)
- heating rate required
- holding time required.

To be commercially successful, ohmic heaters must:

- have effective control of heating and flow rates
- be cost effective

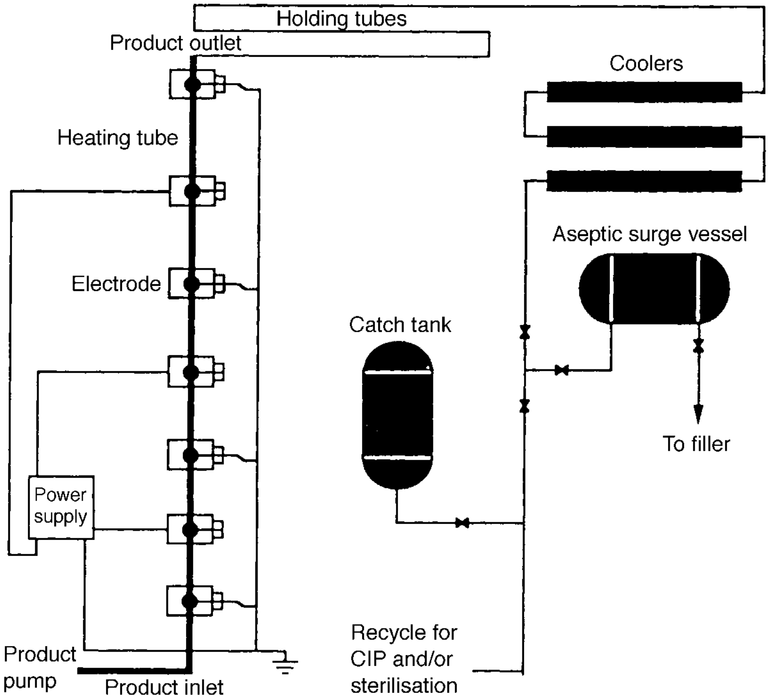


**Fig. 18.6** Flowsheet for ohmic heating system.
(After Parrott (1992).)

- allow aseptic processing and packaging
- have an electrical design that avoids electrolysis or product scorching.

Early designs used DC power, which caused electrolysis (corrosion of electrodes and product contamination) and also had expensive electrodes. The use of mains power supply at 50 Hz reduces the risk of electrolysis and minimises the complexity and cost. Alternatively, higher frequencies (>100 kHz) or carbon electrodes may be used to reduce electrolysis. The layout of the APV Baker ohmic heating system is shown in Fig. 18.6.

Pre-treatments of solid components include:

- pre-heating in the carrier liquid to equilibrate resistances
- blanching pasta for moisture absorption
- heating the carrier liquid to pre-gelatinise starch
- heating to melt and expel fats
- stabilisation of sauces by homogenisation, especially dairy sauces or others that contain fats and heat sensitive proteins
- blanching vegetables to expel air and/or to denature enzymes
- enzymic marinades to soften texture and enhance flavour of meats
- soaking in acids or salts to alter the electrical resistance of particles
- sautéing to improve appearance of meat particles (Zoltai and Swearingen, 1996).

Ohmic heating has been used to process various combinations of meats, vegetables, pasta and fruits when accompanied by a suitable carrier liquid. A variety of shapes, including cubes, discs, spheres, rods and twists have been processed (Zoltai and

Swearingen, 1996). In operation, the bulk of the carrier liquid is sterilised by conventional plate or tubular heat exchangers (Chapter 12) and then injected into the particle stream as it leaves the holding tube. This has the advantage of reducing the capital and operating costs for a given throughput and allows a small amount of carrier liquid to be used to suspend the particles, thus improving process efficiency (Dinnage, 1990). Ohmic heating costs were found by Allen *et al.* (1996) to be comparable to those for freezing and retort processing of low acid products.

Food is pumped up through a vertical tube containing a series of electrodes where it is heated to process temperature. The stainless steel cantilever electrodes (supported from one side) are contained in a PTFE housing and fit across the tube. An alternating current from a 3-phase supply flows between the electrodes and through the food as it moves along the tube. The tube sections are made from stainless steel, lined with an insulating plastic such as polyvinyidene fluoride (PVDF), polyether ether ketone (PEEK) or glass. The system is designed to maintain the same impedance in each section between the electrodes, and the tubes therefore increase in length between inlet and outlet because the electrical conductivity of the food increases as it is heated. Typically, an overall tube dimension of 0.3 cm internal diameter and 30 cm length could heat several hundred litres per hour, whereas a tube of 2.5 cm diameter and 2 m length could heat several thousand litres per hour (Reznick, 1996). Commercial equipment is available with power outputs of 75 and 300 kW, which correspond to throughputs of approximately 750 and 3000 kg $h^{-1}$ respectively (Fryer, 1995). The process is automatically controlled via a feed-forward system (Chapter 2), which monitors inlet temperature, product flow rate and specific heat capacity and continuously adjusts the power required to heat the product (Dinnage, 1990).

The almost complete absence of fouling in ohmic heaters means that after one product has been processed, the plant is flushed through with a base sauce and the next product is introduced. At the end of processing, the plant is flushed with a cleaning solution.

In conventional heaters, turbulence is needed to create mixing of the product and maintain maximum temperature gradients and heat transfer coefficients (Chapter 1, Section 1.3). In ohmic heating, the electric current flows through the product at the speed of light and there are no temperature gradients since the temperature is uniform across the cross-section of flow. The flowrate of product is negligible compared to the velocity of the electric current, but if the flowrate is not uniform across the cross-sectional area, the very high rates of heating mean that slower moving food will become considerably hotter. It is therefore important to ensure that uniform (or 'plug') flow conditions are maintained in the heater. Kim *et al.* (1996) give details of experimental studies which confirm that this takes place. Similarly, the type of pump that is used should provide a continuous flow of material without pulses, as these would lead to increased holding times in the tube and uneven heating. A high pressure is maintained in the heater (up to 4 bar for UHT processing at 140ºC) to prevent the product from boiling. Food then passes from the heater to a holding tube where it is held for sufficient time to ensure sterility and is then cooled and aseptically packaged (also Chapter 12).

The process is suitable for particulate foods that contain up to about 60% solids. In contrast to conventional UHT processing of particulate foods, where the liquid component is an important medium for heat transfer into the particles, in ohmic heating a high solids content is desirable for two reasons: faster heating of low-conductivity particles than the carrier liquid and plug flow in the heater tubes. High solids concentrations can be processed if the particles are pliable and small, or their geometry is varied to reduce the void spaces between particles. Lower concentrations require a higher viscosity carrier liquid to keep the particles in suspension. The density of the particles should also be matched to the carrier liquid: if particles are too dense or the liquid is not sufficiently viscous, the particles will sink in the system and be over-processed. Conversely, if the particles are too light they will float and this leads to variable product composition and the risk of under-processing. It is almost impossible to determine the residence time or heating profiles of particles that float or sink. The viscosity of the fluid (sauce or gravy) should therefore be carefully controlled and for example, pre-gelatinised starches should be used to prevent viscosity changes during processing.

In order for ohmic UHT processing of particulate foods to be accepted by the regulatory authorities, it is necessary to ensure that the coldest part of the slowest heating particle in the food has received sufficient heat to ensure sterility (Chapter 1, Section 1.4.5 and Chapter 12). It is not easy to measure heat penetration into particles, whereas it is relatively easy to measure the temperature of the carrier liquid. The process must therefore demonstrate that solid particles are heated to an equal or greater extent than the liquid when they enter the holding tube. By adjustment of the electrical properties of each component (e.g. by control of salt content in the formulation) it is possible to ensure that this takes place for homogenous particles (Fig. 18.5), but data is not yet available for non-homogenous particles (e.g. fatty meat pieces) which have variable electrical resistance. The situation is made more complex when a batch of food is held before processing and, for example, salt leaches out of the particles into the surrounding sauce. This results in changes to the electrical resistance of both components and hence their rate of heating. Furthermore, the presence of fats and other poorly conductive materials means that particles will heat mostly by conduction and a cold spot will be created within the particle (Larkin and Spinak, 1996). It is important that there is no accidental inclusion of either highly conducting materials, or more likely insulating materials such as pieces of bone, fat, nuts or ice in a food, because neither will be heated. If this happens, the surrounding food may also be under-processed.

Other factors that need to be defined include:

- size and shape of particle pieces
- moisture content of solids
- solids/liquid ratio
- viscosity of liquid component
- amount and type of electrolytes
- pH
- specific heat
- thermal conductivity.

Additionally, the effect of processing on the above factors needs to be determined to detect whether they change and hence alter the heating characteristics of the product. Any changes to ingredients that are made to take account of changing consumer tastes or cost/availability should be tested to determine the effects on heating characteristics (Larkin and Spinak, 1996).

## 18.3 Infrared heating

### 18.3.1 Theory

Infrared energy is electromagnetic radiation (Fig. 18.1) which is emitted by hot objects. When it is absorbed, the radiation gives up its energy to heat materials. The rate of heat transfer depends on:

- the surface temperatures of the heating and receiving materials
- the surface properties of the two materials
- the shapes of the emitting and receiving bodies.

The amount of heat emitted from a *perfect radiator* (termed a *black body*) is calculated using the Stefan–Boltzmann equation:

$$Q = \sigma A T^4 \qquad 18.12$$

where $Q$ ($\mathrm{J\,s^{-1}}$) = rate of heat emission, s = $5.7 \times 10^{-8}$ ($\mathrm{J\,s^{-1}\,m^{-2}\,K^{-4}}$) the Stefan-Boltzmann constant, $A$ ($\mathrm{m^2}$) = surface area and $T$ (K = ºC + 273) = absolute temperature. This equation is also used for a *perfect absorber* of radiation, again known as a *black body*. However, radiant heaters are not perfect radiators and foods are not perfect absorbers, although they do emit and absorb a constant fraction of the theoretical maximum. To take account of this, the concept of *grey bodies* is used, and the Stefan–Boltzmann equation is modified to:

$$Q = \varepsilon \sigma A T^4 \qquad 18.13$$

where $\epsilon$ = emissivity of the grey body (a number from 0 to 1) (Table 18.3). Emissivity varies with the temperature of the grey body and the wavelength of the radiation emitted.

The amount of absorbed energy, and hence the degree of heating, varies from zero to complete absorption. This is determined by the components of the food, which absorb radiation to different extents, and the wavelength of the radiated energy. Some of this radiation is absorbed and some is reflected back out of the food. The amount of radiation absorbed by a grey body is termed the *absorptivity* ($\alpha$) and is numerically equal to the emissivity (Table 18.3). Radiation which is not absorbed is reflected and this is expressed as the *reflectivity* ($1 - \alpha$). There are two types of reflection: that which takes place at the surface of the food and that which takes place after radiation enters the food structure and becomes diffuse due to scattering. Surface reflection produces the gloss observed on polished materials whereas body reflection produces the colours and patterns of a material.

The wavelength of infrared radiation is determined by the temperature of the source. Higher temperatures produce shorter wavelengths which have a greater depth of penetration. The net rate of heat transfer to a food therefore equals the rate of absorption minus the rate of emission:

$$Q = \varepsilon \sigma A (T_1^4 - T_2^4) \qquad 18.14$$

where $T_1$ (K) = temperature of emitter and $T_2$ (K) = temperature of absorber.

**Table 18.3** Approximate emissivities of materials in food processing

| Material | Emissivity |
|---|---|
| Burnt toast | 1.00 |
| Dough | 0.85 |
| Water | 0.955 |
| Ice | 0.97 |
| Lean beef | 0.74 |
| Beef fat | 0.78 |
| White paper | 0.9 |
| Painted metal or wood | 0.9 |
| Unpolished metal | 0.7–0.25 |
| Polished metal | < 0.05 |

From Earle (1983) and Lewis (1990).

*Sample problem 18.1*
An 8 kW oven has a hearth area of 4 $m^2$ and operates at 210ºC. It is loaded with two batches of bread dough in baking tins; 150 loaves on the first batch and 120 loaves on the second batch. The surface of each loaf measures 12 cm × 20 cm. Assuming that the emissivity of dough is 0.85, that the dough bakes at 100ºC, and that 90% of the heat is transmitted in the form of radiant energy, calculate the efficiency of energy use (as the percentage of the supplied radiant energy which is absorbed by the food) for each batch.

*Solution to Sample problem 18.1*
In the first batch,

$$\begin{aligned} \text{area of dough} &= 150(0.2 \times 0.12) \\ &= 3.6\,\text{m}^2 \end{aligned}$$

From equation (18.14)

$$\begin{aligned} Q &= 3.6 \times 0.85\,(5.73 \times 10^{-8})\,(483^4 - 373^4) \\ &= 6145.6\,\text{W} \end{aligned}$$

In the second batch,

$$\begin{aligned} \text{area of dough} &= 120(0.2 \times 0.12) \\ &= 2.88\,\text{m}^2 \end{aligned}$$

and

$$\begin{aligned} Q &= 2.88 \times 0.85\,(5.73 \times 10^{-8})\,(483^4 - 373^4) \\ &= 4916\,\text{W} \end{aligned}$$

Thus, for the first batch,

$$\begin{aligned} \text{efficiency} &= \frac{6145.6}{8 \times 0.9} \\ &= 85\% \end{aligned}$$

and, for the second batch,

$$\begin{aligned} \text{efficiency} &= \frac{4916}{8 \times 0.9} \\ &= 68\% \end{aligned}$$

### 18.3.2 Equipment

Types of radiant heaters include flat or tubular metal heaters, ceramic heaters, and quartz or halogen tubes fitted with electric filaments (Table 18.4).

The main commercial application of radiant energy is in drying low-moisture foods (for example breadcrumbs, cocoa, flours, grains, malt, pasta products and tea) and in baking or roasting ovens (Chapter 16). Products pass through a tunnel, beneath banks of radiant heaters, on a conveyor (Ginzberg, 1969). It is not, however, widely used as a single source of energy for drying larger pieces of food because of the limited depth of penetration. Radiant energy is also used in vacuum band driers and cabinet driers (Chapter 15), in accelerated freeze driers (Chapter 22), in some

**Table 18.4** Infrared emitter characteristics

| Type of emitter | Maximum running temperature (°C) | Maximum intensity (kW m$^{-2}$) | Maximum process temperature (°C) | Radiant heat (%) | Convection heat (%) | Heating–cooling time (s) | Expected life |
|---|---|---|---|---|---|---|---|
| *Short wavelength* | | | | | | | |
| Heat lamp | 2200 | 10 | 300 | 75 | 25 | 1 | 5000 h |
| IR gun | 2300 | 2 | 1600 | 98 | 2 | 1 | – |
| Quartz tube | 2200 | 80 | 600 | 80 | 20 | 1 | 5000 h |
| *Medium wavelength* | | | | | | | |
| Quartz tube | 950 | 60 | 500 | 55 | 45 | 30 | Years |
| *Long wavelength* | | | | | | | |
| Element | 800 | 40 | 500 | 50 | 50 | $< 120$ | Years |
| Ceramic | 700 | 40 | 400 | 50 | 50 | $< 120$ | Years |

From Anon. (1981).

domestic microwave ovens to brown the surface of foods; and to heat-shrink packaging film (Chapter 25).

### 18.3.3 Effect on foods

The rapid surface heating of foods seals in moisture and flavour or aroma compounds. Changes to surface components of foods are similar to those that occur during baking and are described in Chapter 16.

## 18.4 Acknowledgements

Grateful acknowledgement is made for information supplied by: APV Baker Ltd, Peterborough PE4 7AP, UK; The National Committee for Electroheat, London SW1P 4RD, UK; Strayfield International Ltd, Reading RG4 7DW, UK; Raytheon Corporation, Waltham, MA 02154, USA.

## 18.5 References

ALLEN, K., EIDMAN, V. and KINSEY, J. (1996) An economic-engineering study of Ohmic food processing. *Fd. Technol.* **50** (5), 269–273.

ANON. (1981) *The application of infra-red heating to industrial processes*. British National Committee for Electroheat, 30 Millbank, London SW1P 4RD.

BRODY, A. L. (1992) Microwave food pasteurisation, sterilisation and packaging. In: A. Turner (ed.) *Food Technology International Europe*. Sterling Publications International, London, pp. 67–71.

BUFFLER, C. R. (1993) *Microwave Cooking and Processing – engineering fundamentals for the food scientist*. AVI/Van Nostrand Reinhold, New York.

COPSON, D. A. (1975) *Microwave Heating*. AVI, Westport, Connecticut, pp. 262–285.

DECAREAU, R. V. (1985) *Microwaves in the Food Processing Industry*. Academic Press, Orlando, Florida.

DECAREAU, R. V. (1990) Microwave uses in food processing. In: A. Turner (ed.) *Food Technology International Europe*. Sterling Publications International, London, pp. 69–72.

DINNAGE, D. F. (1990) Aseptic processing – use of ohmic heating. In: A. Freed (ed.) *Changing Food Technology* (3). Technomic Publishing, Lancaster, PA, pp. 29–42.

EARLE, R. L. (1983) *Unit Operations in Food Processing*, 2nd edn. Pergamon Press, Oxford, pp. 46–63.

FRYER, P. (1995) Electrical resistance heating of foods. In: G. W. Gould (ed.) *New Methods of Food*

*Preservation*. Blackie Academic and Professional, Glasgow, pp. 205–235.

GARCIA, A. and BUENO, J. L. (1998) Improving energy efficiency in combined microwave-convective drying. *Drying Technology* **16** (1/2), 123–140.

GINZBERG, A. S. (1969) *Applications of Infra-red Irradiation in Food Processing*. Leonard Hill, London.

HUXSOLL, C. C., DIETRICH, W. C. and MORGAN, A. I. (1970) Comparison of microwave and steam or water blanching of corn on the cob. *Fd. Technol.* **24**, 84–87.

JONES, P. L. (1987) Dielectric heating in food processing. In: A. Turner (ed.) *Food Technology International Europe*. Sterling Publications International, London pp. 57–60.

KENT, M. (1987) *Electrical and Dielectric Properties of Food Materials*. Science and Technology Publishers, UK.

KIM, H. J., CHOI, Y. M., YANG, T. C. S., TAUB, I. A., TEMPEST, P., SKUDDER, P., TUCKER, G. and PARROTT, D. L. (1996) Validation of Ohmic heating for quality enhancement of food products. *Fd. Technol.* **50** (5), 253–261.

KLEIN, B. P. (1982) Effect of processing on nutritive value of food: microwave cooking. In: M. Rechcigl (ed.) *Handbook of the Nutritive Value of Processed Food*, Vol. 1. CRC Press, Boca Raton, Florida, pp. 209–236.

LACHANCE, P. A. (1975) Effects of preparation and service of food on nutrients. In: R. S. Harris and E. Karmas (eds) *Nutritional Evaluation of Food Processing*, 2nd edn. AVI, Westport, Connecticut, pp. 463–528.

LARKIN, J. W. and SPINAK, S. H. (1996) Safety considerations for ohmically heated, aseptically processed, multiphase low-acid food products. *Fd. Technol.* **50** (5), 242–245.

LEWIS, M. J. (1990) *Physical Properties of Foods and Food Processing Systems*, Woodhead Publishing, Cambridge, UK.

MOHSENIN, N. N. (1984) *Electromagnetic Radiation Properties of Foods and Agricultural Products*. Gordon and Breach, New York.

MUDGET, R. E. (1982) Electrical properties of foods in microwave processing. *Fd. Technol.* **36**, 109–115.

PARROTT, D. L. (1992) The use of ohmic heating for aseptic processing of food particulates. *Fd. Technol.* **46** (12), 68–72.

RAHMAN, M. S. (1999) Preserving foods with electricity: ohmic heating. In: M. S. Rahman (ed.) *Handbook of Food Preservation*. Marcel Dekker, New York, pp. 521–532.

REZNICK, D. (1996) Ohmic heating of fluid foods. *Fd. Technol.* **50** (5), 250–251.

ROSENBERG, U. and BOGL, W. (1987a) Microwave thawing, drying and baking in the food industry. *Food Technol. (USA)* June 85–91.

ROSENBERG, U. and BOGL, W. (1987b) Microwave pasteurization, sterilization and pest control in the food industry. *Food Technol. (USA)* June 92–99.

SASTRY, S. (1994) Ohmic heating. In: R. P. Singh and F. Oliveira (eds) *Minimal Processing of Foods and Process Optimisation: an interface*. CRC Press, Boca Raton, FL, pp. 17–34.

SASTRY, S. K. and LI, Q. (1996) Modeling the ohmic heating of foods. *Fd. Technol.* **50** (5), 246–247.

SCHIFFMAN, R. F., STEIN, E. W. and KAUFMANN, H. B. (1972) Application of microwave energy to doughnut production. *Fd. Technol.* **25**, 718–722.

STENSTROM, L. A. (1972) *Method and apparatus for sterilisation of heat sensitive products by electromagnetic radiation*, Swedish Patent Appl., No. 352 230.

STENSTROM, L. A. (1973) *Method for heating a product unit in an electromagnetic field of the lowest microwave frequency*, Swedish Patent Appl., No. 355 479.

VON LOESECKE, H. W. (1942) Vegetable preparation and processing. *West. Canner Packer* **34**, 35–38.

ZOLTAI, P. and SWEARINGEN, P. (1996) Product development considerations for ohmic processing. *Fd. Technol.* **50** (5), 263–266.