Part III

New thermal technologies
9

Radio frequency heating
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9.1 Introduction
Radio frequency (RF) or high frequency (HF) heating, is more correctly described as RF dielectric heating, and is a well established thermal processing technology which has found applications in many areas. The most notable of these are found in the plastics (welding), textiles (drying), paper and board (drying), wood (gluing and drying) and food industries. RF heating has much in common with microwave and ohmic heating — all three are electroheat technologies in which heat is generated volumetrically throughout a product rather than having to rely on the slow conduction of heat through its surface.

Following an overview of the fundamentals of RF heating, this chapter will outline why the use of this technology in the food processing industry can lead to clear advantages over other thermal techniques. In particular, the technology will be compared to microwave and ohmic heating. The limitations of the technology will also be discussed. A major section of this chapter describes the technology associated with RF heating and how it is generally used for food processing. Two case studies, RF-assisted baking and meat defrosting, will be presented which emphasise the importance of RF heating to the food processing industry. Finally, the chapter concludes by considering the future direction of the technology, and the implications for the thermal processing of food.

9.2 Basic principles of RF heating
In very simple terms, radio frequency heating of foods arises from the direct conversion of electrical energy to heat within the volume of the food itself. This
electrical energy is provided by a high frequency electric field applied between the plates of a capacitor (the RF applicator). In electrical terms, foods are dielectrics (materials which increase the charge stored in a capacitor) which possess a significant dielectric loss factor (an indication of the amount of energy which will be dissipated).

The term dielectric heating can equally be applied to radio frequency and microwave systems – in both cases the heating is due to the fact that energy is absorbed by a lossy dielectric when it is placed in a high frequency electric field. In foods, at radio frequencies, this loss principally arises from the electrical conductivity of the food, and the heating mechanism is simply resistance heating (i.e. similar to ohmic heating). Although microwave heating also relies on a dielectric loss to provide the heat, the principal loss mechanism in food products at microwave frequencies is different (resonant dipolar rotation).

The radio and microwave frequency bands occupy adjacent sections of the electromagnetic spectrum, with microwaves having higher frequencies than radio waves. The actual dividing point between the two frequency bands is imprecisely defined, with, for example, some applications at around 900 MHz being referred to as RF (cellular telephones), and some as microwaves (dielectric heating). However, the technology used to generate and transmit the high frequency electric fields can be used to distinguish them. RF systems are generally based on high power electrical valves (to produce the RF power), transmission lines (to carry the RF energy), and applicators in the form of capacitors; whereas microwave systems use magnetrons (to generate the microwaves), waveguides (to transport the microwaves) and cavities (in which the microwaves are applied).

There is a relatively small number of internationally agreed and recognised frequency bands which can be used for RF and microwave heating. These are known as the Industrial, Scientific and Medical (ISM) bands, and are defined in Table 9.1. Electromagnetic compatibility (EMC) regulations set very low limits for any emissions outside of these bands, and, in most countries, compliance is a legal obligation. Consequently, virtually all RF process heating equipment will operate at one of the three allowed ISM frequencies. It is worthwhile noting that the wavelength at radio frequencies is substantially greater than at microwave frequencies – 11 m at 27.12 MHz compared with only 12 cm at 2450 MHz. It is this difference which leads to a number of significant advantages of RF over microwaves, particularly for industrial food processing applications.

**Table 9.1** The ISM bands available for dielectric heating

<table>
<thead>
<tr>
<th>Heating technology</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>Radio frequency</td>
<td>13.56 MHz ± 0.05% (± 0.00678 MHz)</td>
</tr>
<tr>
<td></td>
<td>27.12 MHz ± 0.6% (± 0.16272 MHz)</td>
</tr>
<tr>
<td></td>
<td>40.68 MHz ± 0.05% (± 0.02034 MHz)</td>
</tr>
<tr>
<td>Microwave</td>
<td>~900 MHz (depending on country)</td>
</tr>
<tr>
<td></td>
<td>2450 MHz ± 50 MHz</td>
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A calculation of the actual amount of energy (or power) absorbed by a dielectric body is essential to a full understanding of radio frequency (or microwave) heating. An expression for the power dissipated in a dielectric can be derived following directly from the premise that, in essence, all applicators used for RF dielectric heating are some form of capacitor. When a dielectric material such as food (with a dielectric constant, $\varepsilon_r'$, and a dielectric loss factor, $\varepsilon_r''$) is placed in this capacitor, it will be affected in two ways (see Fig. 9.1). First, the new effective capacitance, $C'$, will be greater than the original capacitance ($C_o$) by a factor $\frac{1}{C_0}$ (by definition, $\varepsilon_r'$ is always greater than one), and secondly, a finite resistance, $R$ (proportional to $1/C_0\varepsilon_r''$), will appear across the capacitor.

The increase in capacitance arises from a change in the distribution of electric charge within the RF applicator, and the presence of the resistance gives the possibility of heat generation within the dielectric. Assuming that the power, $P$, dissipated in this resistance to be equal to $V^2/R$, then it can be shown that the power dissipation per unit volume or power density, $P_v$, is given by:

$$P_v = 2\pi f\varepsilon_0\varepsilon_r''E^2$$  \[9.1\]

where $f$ is the frequency of the applied field (RF), $\varepsilon_0$ is a constant (the permittivity of free space) and $E$ is the electric field strength in the dielectric.

Although derived in another way, the same equation is used to describe microwave dielectric heating.\(^5\) Inspection of equation [9.1] reveals that the power density is proportional to the frequency of the applied field and the dielectric loss factor, and is proportional to the square of the local electric field. This equation is crucial in determining how a dielectric will absorb energy when it is placed in a high frequency electric field. For a given system, the frequency is fixed and $f$ and $\varepsilon_0$ are both constants. The dielectric loss factor $\varepsilon_r''$ can, in principle, be measured. The only unknown left in equation [9.1] is the electric field, $E$. To evaluate this, the effect of the dielectric material itself on the applied electric field (due to the RF voltage across the RF applicator) must be considered.

For materials, such as food products, where the dielectric loss arises principally from the electrical conductivity, then the loss factor, $\varepsilon_r''$, is given by $\varepsilon_r'' = \sigma/2\pi f\varepsilon_0$, and equation [9.1] can be further reduced to

$$P_v = \sigma E^2$$  \[9.2\]
which is the same equation as that used to describe ohmic heating. However, unlike ohmic heating, in RF heating this electric field can be achieved without the need for the electrodes to be in contact with the product. This is a consequence of the much higher frequency used.

9.3 Application to food processing

Radio frequency heating has been used in the food processing industry for many decades. In particular, RF post-baking of biscuits and cereals, and RF drying of foods are well established applications. More recently, RF thawing equipment has demonstrated substantial benefits over conventional techniques and over comparable microwave tempering systems. Furthermore, as the public concern over food safety issues continues to grow, and as the demand for convenience foods increases, RF pasteurisation and sterilisation processes are becoming more important.

9.3.1 Baking

The post-baking of biscuits is one of the most accepted and widely used applications of RF heating in the food processing industry. The addition of a relatively small RF unit to the end of a conventional baking line results in a substantial increase in product throughput, together with improvements in product quality. Similarly, the same process has also been applied to cereal, pastry and bread products. More recently, the RF system has been incorporated directly into the hot air oven, allowing RF-assisted baking of a wide range of products to be carried out in a very compact unit.

9.3.2 Drying

The principal role of RF heating in baking is the removal of moisture, particularly at the end of the process when conventional heating is inefficient. RF drying is intrinsically self-levelling, with more energy being dissipated in wetter regions than in drier ones. This RF levelling leads to improvements in product quality and more consistent final products. As well as baking applications, RF drying applications in the food industry include the drying of: food ingredients (e.g. herbs, spices, vegetables); potato products (e.g. French fries), and a number of pasta products.

9.3.3 Defrosting

A more recent, and rapidly growing, application of RF in the food processing industry is its use for the bulk defrosting of meats and fish. Conventionally, large blocks of meat are thawed slowly, often over a period of days. The volumetric nature of RF heating allows the thawing process to be accelerated, whilst still
maintaining control of the temperature distribution within the food product. Typically, RF defrosting times of 1–2 hours are possible.

9.3.4 Pasteurisation/sterilisation
With the increasing demand for convenience foods and ‘ready meals’, re-heating of food products is becoming more common, often carried out in a microwave oven, and it can no longer be assumed that all of the food is heated to a high enough temperature to kill bacteria. Consequently, there is a demand for more in-package pasteurisation. As a non-contact volumetric heating technique, RF is an ideal process for this application. Increased public concern and awareness of food safety issues are leading to more RF pasteurisation and sterilisation applications being investigated, and it is likely that a number of these will become industrial processes in the near future.

9.4 Advantages and disadvantages of RF heating
9.4.1 Advantages
In common with microwave and ohmic heating, the volumetric nature of radio frequency heating gives rise to a number of significant advantages over more traditional, surface heating techniques. The most important of these to the food industry are:

- **Improved food quality.** The main reason for using RF heating in food processing (rather than any other thermal technology) is improved food quality. First, the volumetric process leads to more uniform heating, removing the risk of overheating food surfaces while trying to heat the centre of products. Secondly, the selective nature of RF heating, with energy being dissipated according to the local loss factor, can produce very uniform products, even when there are relatively large variations in the unprocessed food.

- **Increased throughput.** Conventional surface heating often has to heat foods relatively slowly to avoid the risk of overheating the surface. Moreover, once the surface of foods have dried out, they often form a good thermal barrier layer, making it even more difficult to heat the centres. By contrast, volumetric RF heating avoids these effects, allowing production lines to operate much faster.

- **Shorter process lines.** As an alternative to increased throughput, food processing lines which include RF systems can be significantly shorter for a given throughput.

- **Improved energy efficiency.** Since the RF energy is dissipated directly within the product being heated, processing lines using this technology can be very efficient, particularly when the increased throughput is also taken into account.
Improved control. Since the power dissipated within the food is due to the presence of an electric field (equation [9.1]), if this field is changed, or switched off, the heating of the food products responds almost instantaneously. In this way, RF heating can be controlled very precisely, again leading to improvements in food quality.

In food processing, RF heating also has a number of advantages over the alternative volumetric technologies, namely microwave and ohmic heating. The main ones are:

- **Contactless heating.** Although the heating mechanism is essentially the same as with ohmic heating, RF does not require the electrodes to be in contact with the food. This removes the constraint that the food product has to be pumpable, and allows RF heating to be applied to solid as well as liquid heating.

- **Increased power penetration.** The longer wavelength at radio frequencies compared with microwave frequencies, and the dielectric properties of foods, mean that RF power will penetrate further into most products than microwave power. For example, the penetration depth (the distance for the power to fall to $1/e$ of its initial value) in unfrozen meat products is typically only a few millimetres at microwave frequencies, but tens of centimetres at RF frequencies.

- **Simpler construction.** Large RF applicator systems are generally simpler to construct than microwave ones. In particular, the longer wavelength at radio frequencies allows relatively large entry and exit ports to be designed – 2 m wide ports are not untypical. Moreover, the geometries of RF applicator systems (see Section 9.5.3) naturally lend themselves to industrial food processing applications.

- **Improved moisture levelling.** In food products, the variation of the dielectric loss factor with moisture content is generally greater at radio than at microwave frequencies. Consequently, the use of RF heating for baking and drying applications leads to improved moisture levelling and correspondingly higher quality final products.

### 9.4.2 Disadvantages

When compared with conventional heating techniques, and, to some extent with ohmic heating, the main disadvantages of RF heating relate to equipment and operating costs. In comparison with microwave heating, the main limitation of RF heating arises from a lower power density.

- **Equipment and operating cost.** For an equivalent power output, RF heating equipment is more expensive than conventional convection, radiation or steam heating systems. It is also more expensive than an equivalent ohmic heating system. However, in some applications, improvements in product quality and throughput often more than justify the initial capital investment.
As an electroheat technology, the unit energy costs of a RF system will be higher than an equivalent conventional heating system. Nevertheless, when factors such as increased energy efficiency and increased throughput are taken into account, the total energy cost may be comparable to (or even less than) a conventional system.

1. Reduced power density. Equation [9.1] shows that the power density is directly proportional to the frequency. Given that the electric field is limited to avoid the occurrence of an electrical breakdown, then the power density will be much higher at microwave than radio frequencies. The main consequences of this are that RF systems are usually significantly larger than microwave heating systems of the same power rating, and that faster heating rates can often be achieved with a microwave system.

9.5 RF heating technologies

The available systems for producing and transferring RF power to dielectric heating applicators can be divided into two distinct groups; the more widespread conventional RF heating equipment, and the more recent 50Ω RF heating equipment. Although conventional RF equipment has been used successfully for many years, the ever tightening EMC regulations, and the need for improved process control, are leading to an increased use of RF heating systems based on 50Ω technology.

9.5.1 Conventional RF equipment

In a conventional system, the RF applicator (i.e. the system which applies the high frequency field to the product) forms part of the secondary circuit of a transformer which has the output circuit of the RF generator as its primary circuit. Consequently, the RF applicator can be considered to be part of the RF generator circuit, and is often used to control the amount of RF power supplied by the generator. In many systems, a component in the applicator circuit (usually the RF applicator electrodes themselves) is adjusted to keep the power within set limits. Alternatively, the heating system is set up to deliver a certain amount of power into a standard load of known conditions, and then allowed to drift automatically up or down as the condition of the product changes. In virtually all conventional systems, the amount of RF power being delivered is only indicated by the DC current flowing through the high power valve (usually a triode) within the generator. A typical conventional RF heating system is shown schematically in Fig. 9.2.

9.5.2 50Ω RF equipment

RF heating systems based on 50Ω equipment are significantly different, and are immediately recognisable by the fact that the RF generator is physically separated from the RF applicator by a high power coaxial cable (Fig. 9.3).
The operation frequency of a 50 Ω RF generator is controlled by a crystal oscillator and is essentially fixed at exactly 13.56 MHz or 27.12 MHz (40.68 MHz is seldom used). Once the frequency has been fixed, it is relatively straightforward to set the output impedance of the RF generator to a convenient value – 50 Ω is chosen so that standard equipment such as high power cable and RF power meters can be used. For this generator to transfer power efficiently, it must be connected to a load which also has an impedance of 50 Ω. Consequently, an impedance matching network has to be included in the system which transforms the impedance of the RF applicator to 50 Ω. In effect, this matching network is a sophisticated tuning system, and the RF applicator plates themselves can be fixed at an optimum position.
The main advantages of this technology over the conventional systems are:

- Fixed operation frequency makes it easier to meet onerous international EMC regulations.
- The use of 50Ω cable allows the RF generator to be placed at a convenient location away from the RF applicator. This is of particular importance to food processing applications, where the RF applicator will need to be cleaned regularly.
- The RF applicator can be designed for optimum performance, and is not itself part of any tuning system.
- The use of a matching network gives the possibility of an advanced process control system. The positions of components in the matching network give on-line information on the condition of the dielectric load (such as its average moisture content). This information can be used to control the RF power, the speed of conveyor or the temperature of air in applicator as appropriate.

9.5.3 RF applicators
Whether conventional or 50Ω dielectric heating systems are used, the RF applicator has to be designed for the particular product being heated or dried. Although the size and shape of the applicator can vary enormously, they mostly fall into one of three main types – throughfield, fringefield or staggered throughfield.

Whatever the type of applicator, RF food processing systems often benefit from the combination of RF with hot air convection heating. This hot air can either be introduced conventionally into the applicator enclosure, or directed onto the surface of the product through the electrodes themselves. This combination of volumetric and conventional surface heating optimises the cooking, baking and drying processes in such a way that relatively small amounts of RF energy can lead to large improvements in throughput and food quality, whilst minimising the size of the combination heating unit.

**Throughfield applicator**
Conceptually, a throughfield RF applicator is the simplest, and the most common, design, with the electric field originating from a high frequency voltage applied across the two electrodes which form a parallel plate capacitor (Fig. 9.4a). This type of system can be used for both batch and continuous processing applications, and is mainly used with relatively thick products, or blocks of material. For example, this electrode arrangement is found in RF meat defrosting systems.

**Fringefield applicator**
An alternative RF applicator arrangement, often used in drying applications, is known as the fringefield system. In this case, the product passes over a series of bars, rods or narrow plates which are alternately connected to either side of the
Fig. 9.4 Alternative RF electrode configurations.
RF voltage supply (Fig. 9.4c). The major advantage of this configuration is that the product runs close to the electrode bars and there is only a small air gap between the RF applicator and the product. This ensures that there will be a virtually constant electric field in the material between the bars (an important requirement to maximise moisture levelling performance). It also reduces the electric field that has to be applied between the electrodes to generate a given power density within the product. The major disadvantage of this arrangement is that only relatively thin layers of product can be used, otherwise there will be an electric field variation throughout the product thickness. This electrode arrangement is found in some pasta drying and cereal baking applications.

**Staggered throughfield applicator**
For intermediate thickness products, a modified form of the throughfield applicator is often used. This is known as a staggered throughfield applicator (Fig. 9.4b). This arrangement reduces the overall capacitance of the applicator which, in turn, makes the overall system tuning easier. It also reduces slightly the voltage that has to be applied across the electrodes to produce a given RF power density within the product. This electrode configuration is commonly used in RF post-baking applications.

### 9.6 Case studies

#### 9.6.1 RF-assisted biscuit baking

**Conventional process**
In a conventional baking oven, convective and/or radiative energy is applied simultaneously to the top and bottom surface of the biscuits. The biscuit drying proceeds from these surfaces towards the biscuit centre. Once the surface has dried the conventional heat starts to bake the surface. A typical industrial biscuit baking oven is about 60 m long. The main disadvantages arise from the difficulty associated with the use of conventional surface heating to remove the small amount of moisture in the centre of the biscuit at the end of the process. These are:

- the biscuit baking line has to be very long, due to the disproportionately high amount of energy needed towards the end of the biscuit baking process
- for the same reason, conventional biscuit baking is very energy intensive
- the conventional process leads to only average or even poor quality biscuits.

**RF process**
The traditional RF solution to these problems is to add a relatively small (3–4 m long) RF drying unit at the end of the conventional processing line. The intrinsic moisture levelling associated with RF heating allows the final thin layers of moisture at the centre of the biscuit to be rapidly and efficiently removed. Such a RF post-baking unit can increase throughput by up to 30%. More recently, the
RF applicator systems have been incorporated directly into the conventional high temperature ovens allowing hot air and RF energy to be applied simultaneously. This RF-assisted biscuit baking system is comprised of a number of RF zones, with typically 40–50 kW of RF power per zone. The main advantages of the RF-assisted unit, over both conventional and RF post-baking systems, are:

- the length of the biscuit oven can be substantially shorter
- it is a very energy efficient process
- biscuit quality is substantially improved: the biscuits are typically larger, have a less dense and more uniform structure, are more difficult to break and have a less 'pasty' taste.

9.6.2 Meat defrosting

Conventional process

Once removed from cold storage, large (typically 10–20 kg) blocks of meat have to be carefully stacked in a temperature controlled room where they slowly thaw out over a period of several days. Even at this slow thawing rate, there is often a large variation in temperature within individual blocks and between different blocks. The main disadvantages of the conventional process are:

- the slow processing speed means that the supply of defrosted meat cannot respond to a rapidly changing demand
- during conventional thawing, there is a large drip loss from the meat which can account for up to 12% of the product volume, and which reduces significantly the value of the product (meat is sold by weight), and also gives effluent handling problems
- the conventional process is very labour intensive
- the slow thawing process can lead to significant biological growth which reduces the product shelf-life, and may present a potential health risk
- a large amount of floor space has to be allocated to the thawing process.

RF process

The RF meat defroster is a continuous, conveyorised unit made up of three independent RF zones, each with a relatively simple throughfield electrode arrangement. A generator with a maximum output power of typically 30–40 kW is connected to each zone. This RF unit can continuously defrost around one tonne of meat per hour, with a defrost time of less than two hours. A typical unit would be around 20 m long with a conveyor belt width of about 2 m. The main advantages of the RF meat defroster are:

- with a thawing time of less than 2 hours, the RF unit allows the supply of thawed meat to respond rapidly to any changes in demand
- the drip loss is reduced to less than 1% – increasing the value of the final product and reducing any effluent handling problems
• any biological growth is minimised, increasing the shelf-life of the meat products, and reducing any health hazard
• the RF defrosting process is not labour intensive – up to 75% less than the conventional process
• compared with the conventional thawing process, the RF unit is very compact.

9.7 Future trends in RF heating

The future direction of the use of RF heating in the food processing industry will be influenced by many factors. Developments in RF technology could significantly benefit both existing and emerging food applications. Similarly, changes in consumer food preferences could lead to new applications, but could also lead to some existing applications becoming redundant. Moreover, changes in the food (or radio) regulations could have a major impact on the future use of RF heating in the food industry.

9.7.1 Technology

Although predicting the future direction of any technology is, at best, difficult, there are a number of general trends in RF heating technology which are likely to influence food processing applications.

50 Ω RF equipment specifically developed for the dielectric heating market is now commercially available, and the technology has been proven for a range of food applications. The clear benefits of this technology over conventional equipment (see Section 9.5.2) will lead to its more widespread future use, both for new processing lines, and as replacements for conventional RF equipment in existing lines.

At present, virtually all RF generators used for the thermal processing of foods use thermionic valves. However, future developments in transistor technology (particularly in MOSFETs), will lead to the upper power limit of solid state generator systems being increased from its present level of 5–10 kW. Ultimately, cost competitive solid state generators will be available in the range 20–50 kW typically used in most industrial food processing applications. Such RF generators will be compact, light and very controllable.

The same developments in transistor technology could also lead to low power (i.e. 0.5–2 kW) RF generators becoming much cheaper. At present, microwave heating completely dominates dielectric heating in the commercial (and domestic) food processing sectors. Even though RF heating has a number of clear advantages over microwave heating (see Section 9.4.1), the cost of low power RF systems is prohibitively expensive compared to equivalent microwave systems. The availability of low cost RF power sources could lead to a major growth in the use of RF heating in the commercial food sectors.
9.7.2 Applications
The current and increasing demand for high quality food products will mean that RF post-baking and RF-assisted baking will continue to be important stages in the processing of biscuit, cereal and pastry products. Similarly, public concern over food hygiene issues will continue to require rapid and safe food thawing techniques, such as RF meat and fish defrosting systems. Increasing public awareness of general food safety issues, and the rising demand for convenience, pre-packaged foods will lead to a growth in the demand for RF (and microwave) pasteurisation and sterilisation techniques.

9.8 Sources of further information and advice

9.8.1 Further reading
HULLS P (Secretary, dielectric heating working group), Dielectric Heating for Industrial Processes, UIE, 1992.

9.8.2 Organisations and other contacts
EA Technology
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EA Technology provide advice and supply RF heating equipment to the food industry. They also have expertise in microwave and ohmic heating systems.

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9.10 References