10

Microwave processing

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10.1 Introduction

In this chapter an overview of microwave heating as one method of thermal food processing is presented. Due to the limited space, this overview cannot be complete; instead some important theoretical information and also examples of practical uses at home and in industry are shown. This chapter provides a starting point, and the interested reader is directed to the references, where more information about the special themes discussed in this chapter can be found. Additional to the references in the text the interested reader is also referred to two bibliographies that cover more or less all the published work on microwaves (Goldblith and Decareau 1973; Dehne 1999).

10.1.1 History of microwave heating

The total sales number of microwave ovens in the United States stays at a constant level of approximately 10 million per year (Anon. 1998). The corresponding number in Europe is in the same range. These enormous sales point to the importance of microwave heating today. Nevertheless, it took some time for the development of this technique starting from the microwave source invention in 1921 by Hill (Knutson *et al.* 1987). The first continuous magnetron (see Section 10.2.4) was built by Randall and Boot who tried to produce a microwave source to power radar sets for the British military during World War II (Reynolds 1989). It was brought to the United States in order to use America's production potential. Raytheon Co. was the company that received a contract to make copies of the magnetron, where the electrical engineer Spencer improved its manufacturability for large productions. He filed a patent in 1942 concerning the ameliorated magnetron that was issued nine years later. In 1945 Spencer occasionally observed the heating of various substances (a legend tells about his own body, popcorn and an exploding egg) by the microwave energy of the antenna horn (Reynolds 1989). In the same year, he applied for a patent (issued in 1950) called 'method of treating foodstuffs' describing for the first time a closed microwave oven. This technique was applied in Raytheon's Radarange oven in 1946. With further development and falling prices (also due to the expiring of the basic patent) the domestic microwave oven market grew very fast, starting in the late 1960s, reaching a peak of 12 million ovens sold in the United States in 1988, later becoming constant near 10 million per year.

The development of industrial dielectric heating applications started in the radio frequency range in the 1930s (Püschner 1966). Due to the proportionality of the electromagnetic power loss to the used frequency (see equation [10.24]) the energy rate could be enhanced by increasing the frequency. The first patent describing an industrial conveyor belt microwave heating system was issued in 1952 (Spencer 1952). However, the first conveyor belt microwave application only started in 1962 due to the slow development of high power microwave generators. Its first major applications were the finish drying of potato chips, pre-cooking of poultry and bacon, tempering of frozen food and drying of pasta (Decareau 1985).

10.1.2 Today's uses, advantages and disadvantages of microwave heating applications

Today's uses range from these well known applications over pasteurisation and sterilisation to combined processes like microwave vacuum drying (see also Section 10.3). The rather slow spread of food industrial microwave applications has a number of reasons: there is the conservatism of the food industry (Decareau 1985) and its relatively low research budget. Linked to this, there are difficulties in moderating the problems of microwave heating applications. One of the main problems is that, in order to get good results, they need a high input of engineering intelligence. Different from conventional heating systems, where satisfactory results can be achieved easily by intuition, good microwave application results often do need a lot of knowledge or experience to understand and moderate effects like uneven heating (e.g. edge heating or focused heating) (see Section 10.2.2), or the thermal runaway (see Section 10.2.3)). Another disadvantage of microwave heating as opposed to conventional heating is the need for electrical energy, which is its most expensive form.

Nevertheless, microwave heating has a number of quantitative and qualitative advantages over conventional heating techniques that make its adoption a serious proposition. One main advantage is the place where the heat is generated, namely the product itself. Because of this, the effect of small heat conductivities or heat transfer coefficients do not play such an important role. Therefore, larger pieces can be heated in a shorter time and with a more even temperature distribution. These advantages often yield an increased production rate and/or an improved product quality. Another advantage is the almost entire energy conversion from electromagnetic radiation into heat, where it is needed. Depending on the various applications, there could be further advantages like space savings or low noise levels.

10.2 Physical principles

10.2.1 MW-frequency range

Microwaves are a kind of electromagnetic wave within a frequency band of 300 MHz to 300 GHz. By equation [10.1] the frequency f is linked by the velocity of light c to a corresponding wavelength λ.

$$c = \lambda \cdot f \tag{10.1}$$

The term microwaves is a little bit misleading since the vacuum wavelength of them is in the range between 1 m and 1 mm. Their name rather points to their wavelength within the matter, where their wavelength can be in the micrometer range. In practice, for microwave heating applications not all the microwave spectrum is used, in effect there are some discrete frequency bands, which have been set aside from telecommunication applications for industrial, scientific and medical (so called ISM) applications. The most important and most used ISM microwave frequency bands are 915 ± 25 MHz and 2450 ± 50 MHz, where a certain limited radiation level has to be tolerated by other applications (like communication devices).

10.2.2 Maxwell's equations, wave equations and exemplary solutions

Maxwell's equations

As already mentioned above, microwaves belong to electromagnetic waves, which can be basically described with Maxwell's equations [10.2–10.5]:

$$\nabla \cdot \vec{D} = \rho \tag{10.2}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{10.3}$$

$$\nabla \cdot \vec{B} = 0 \tag{10.4}$$

$$\nabla \times \vec{H} = \left(\vec{j} + \frac{\partial \vec{D}}{\partial t}\right) \tag{10.5}$$

In order to include the interactions of matter with electromagnetic fields, the material equations, also called constitutive relations [10.6–10.8], have to be added, where the permittivity or dielectric constant ε (interaction of non-conducting matter with an electric field), the conductivity σ and the permeability μ (interaction with a magnetic field) appear to model their behaviour (see also Section 10.23). The zero indexed values describe the behaviour of a vacuum, so that ε and μ are relative values.

$$\vec{D} = \varepsilon_0 \, \varepsilon \cdot \vec{E} \tag{10.6}$$

$$\vec{B} = \mu_o \, \mu \cdot \vec{H} \tag{10.7}$$

$$\vec{j} = \sigma \cdot \vec{E} \tag{10.8}$$

In the most general form all these material parameters, describing the properties of matter, can be complex tensors (with directional dependent behaviour). For practical use with food substances some simplifications are possible: the relative permeability can be set to $\mu = 1$, since food behaves non-magnetically, and the permittivity tensor can be reduced to a complex constant with real (ε') and imaginary part (ε''), which may include the conductivity σ (see Section 10.2.3).

Wave equations and exemplary solutions

Starting from Maxwell's equations, with the simplifications of no charge ($\rho = 0$) and no current density ($\vec{j} = 0$), there is an easy way to infer the wave equations for electric and magnetic fields (here only shown for the electric field case). Applying the curl-operator ($\nabla\times$) on [10.3] yields [10.9]:

$$\nabla \times (\nabla \times \vec{E}) = -\nabla \times \frac{\partial \vec{B}}{\partial t} = -\frac{\partial}{\partial t}(\nabla \times \vec{B}) \tag{10.9}$$

Using the material equation for the magnetic field [10.7], supposing μ to be constant and introducing [10.5] into [10.9], this can be transformed to [10.10]:

$$\nabla \times (\nabla \times \vec{E}) = -\mu_0 \mu \frac{\partial}{\partial t}\left(\frac{\partial \vec{D}}{\partial t}\right) \tag{10.10}$$

The last step is to utilise the material equation for the electric field [10.6], Maxwell's equation [10.2] and the vector identity $\nabla \times (\nabla \times \vec{X}) = \nabla(\nabla \cdot \vec{X}) - \Delta\vec{X}$ to get the following well known wave equation [10.11]:

$$\Delta\vec{E} - \mu_0 \mu \, \varepsilon_0 \, \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \tag{10.11}$$

Similarly the corresponding wave equation for the magnetic component can be derived, yielding [10.12]:

$$\Delta\vec{B} - \mu_0 \mu \, \varepsilon_0 \, \varepsilon \frac{\partial^2 \vec{B}}{\partial t^2} = 0 \tag{10.12}$$

By comparing the wave equations [10.11] and [10.12] with the standard one, one can infer that in this case the wave velocity is defined by [10.13]:

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0 \mu \varepsilon}} = \frac{c_0}{\sqrt{\mu \varepsilon}} \tag{10.13}$$

In order to illustrate the nature of solutions of [10.11] or [10.12], we consider the case where the electric field has only a component in the z-direction E_z (so-called linearly polarised) and depends only on the x coordinate (so-called plane wave). Additionally the material parameters should be frequency independent. Equation [10.11] then reduces to

$$\frac{\partial^2 E_z}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2} = 0 \qquad [10.14]$$

Often used as solutions also for the more complex case [10.11], [10.12] are time harmonic functions:

$$\vec{E} = \vec{E}_0 \cos(\vec{k}\vec{x} - \omega t),$$

$$\vec{E} = \vec{E}_0 \sin(\vec{k}\vec{x} - \omega t),$$

$$\vec{E} = \Re\left[\vec{E}_0 \exp\left\{i(\vec{k}\vec{x} - \omega t)\right\}\right] \qquad [10.15]$$

Here $\vec{k}$ is the wave vector pointing to the direction of propagation with its absolute value defined by

$$\vec{k}^2 = \frac{\omega^2}{c^2} \qquad [10.16]$$

It should be added that the magnetic and the electric field are not independent from each other, since the wave equations cannot completely replace Maxwell's equations. These lead to further conditions listed in Table 10.1.

Both the dispersion (the dependence of c on ω) and the absorption are included in this theory, the latter by a complex permittivity and with this a complex wave vector. Another case of absorption occurs when a current $\vec{j} = \sigma \cdot \vec{E}$ is allowed due to finite conductivity σ in [10.10]. Then [10.11] becomes:

$$\Delta\vec{E} - \mu_0\mu\,\sigma\frac{\partial^2\vec{E}}{\partial t} - \mu_0\mu\,\varepsilon_0\varepsilon\frac{\partial^2\vec{E}}{\partial t^2} = 0 \qquad [10.11a]$$

Using time-harmonic functions for the electric field as above, [10.11a] reduces to:

$$\Delta\vec{E} + \omega^2\mu_0\mu\varepsilon_0\left(\varepsilon - i\frac{\sigma}{\varepsilon_0\omega}\right)\vec{E} = 0 \qquad [10.11b]$$

This equation shows that a finite conductivity σ is equivalent to an imaginary term in the permittivity ε.

Coming back to an exemplary solution, the time harmonic plane wave in the case of an absorbing material, where the permittivity ε has an imaginary part $\varepsilon = \varepsilon' - i\varepsilon''_{\text{total}}$,

Table 10.1 Further conditions on electric and magnetic fields of an electromagnetic wave

Transversality	Correlation of electric and magnetic fields
$\vec{k} \cdot \vec{E}_0 = 0$	$\vec{k} \times \vec{E}_0 = \omega\vec{B}_0$
$\vec{k} \cdot \vec{B}_0 = 0$	$\vec{k} \times \vec{B}_0 = -\omega\mu_0\mu\varepsilon_0\varepsilon\vec{E}_0$

Table 10.2 Boundary conditions for the electric and the magnetic fields, which have to be satisfied by the wave solutions at the boundaries

Prerequisite	Boundary condition
No surface charge	Continuity of $D_\perp$
–	Continuity of $B_\perp$
No surface current	Continuity of $H_{\|\|}$
–	Continuity of $E_{\|\|}$
Ideally conducting wall (metallic)	$E_{\|\|} = 0$
Ideally conducting wall (metallic)	$B_\perp = 0$

$$\varepsilon''_{\text{total}} = \varepsilon'' + \frac{\sigma}{\varepsilon_0 \omega} \qquad [10.17]$$

has to be a solution of [10.11c].

$$\frac{\partial^2 E_z}{\partial x^2} + \omega^2 \mu_0 \mu \varepsilon_0 (\varepsilon' - i\varepsilon''_{\text{total}}) E_z = 0 \qquad [10.11c]$$

A similar equation can be derived for the magnetic component of the plane wave, leading to a general solution with g, h, m and n constants to satisfy the boundary conditions (see Table 10.2):

$$\begin{aligned} E_z &= g \cdot \exp\{(ik + \kappa)x\} + h \cdot \exp\{-(ik + \kappa)x\} \\ H_y &= m \cdot \exp\{(ik + \kappa)x\} + n \cdot \exp\{-(ik + \kappa)x\} \end{aligned} \qquad [10.18]$$

One boundary condition, namely the continuity of $E_{||}$ has to be emphasised, since it can explain the often observed effect of edge or corner overheating. Later it will be shown that the power dissipation in a sample volume is proportional to the squared electric field [10.24]. At edges (corners) the microwaves cannot only intrude from two (three) directions, but also at these volumes electric fields of two (three) polarisations find a parallel surface to intrude continuously, which means without amplitude decrease. Therefore the heat generation there will be very large.

The solution [10.18] is an exponentially damped wave, with wave number k and damping constant κ, where the dependency on ε can be derived by solving

$$\omega^2 \mu_0 \mu \varepsilon_0 (\varepsilon' - i\varepsilon''^*) = (\kappa + ik)^2 \qquad [10.19]$$

leading to

$$k = \omega \sqrt{\frac{\mu_o \mu \varepsilon_0 \varepsilon'}{2}} \cdot \left(\sqrt{\sqrt{1 + \frac{\varepsilon''^{*2}}{\varepsilon'^2}} + 1} \right) \qquad [10.20]$$

and

$$\kappa = \omega \sqrt{\frac{\mu_o \mu \varepsilon_0 \varepsilon'}{2}} \cdot \left(\sqrt{\sqrt{1 + \frac{\varepsilon''^{*2}}{\varepsilon'^2}} - 1} \right) \qquad [10.21]$$

The corresponding electric field penetration depth, the distance in which the electric field is reduced to 1/*e* is defined by $\delta_{e1} = 1/\kappa$.

An important consequence of the frequency dependency of κ is that microwaves of 915 MHz do have an approximately 2.5 times larger penetration depth than waves of 2450 MHz, when similar permittivities at both frequencies are assumed.

With the assumption of the excitation and the propagation of a plane wave, that satisfies the boundary conditions, first estimations of the field configurations are possible. This yields, for example, the laws of the geometric optics, which are also valid for microwaves, when a typical object size is much larger than the wavelength. With this approach the particular centre heating of objects of cm-dimensions with convex surfaces (like eggs) can be easily understood, since at the convex surface the microwave 'rays' are refracted and focused to the centre.

In order to calculate the temperature change within an object by microwave heating, it is important to determine the power density, starting from the electromagnetic field configuration. Since normal food substances are not significantly magnetically different from vacuum ($\mu = 1$), in most cases the knowledge of the electric field is enough to calculate the heat production, by power dissipation. This power dissipation (per unit volume) p_V is determined by ohmic losses which are calculable by

$$p_V = \frac{1}{2}\Re(\vec{E} \cdot \vec{j}^{\,*}) \qquad [10.22]$$

The value of current density is determined by the conductivity and the electric field $\vec{j} = \sigma_{\text{total}} \cdot \vec{E}$. As in equation [10.17] the equivalence of an imaginary part of the permittivity and a conductivity is shown, here the conductivity also consists of the pure d.c. conductivity σ and the imaginary part of the permittivity ε:

$$\sigma_{\text{total}} = \sigma + \omega\varepsilon_0\varepsilon'' \qquad [10.23]$$

The resulting power dissipation can be written in terms of the total conductivity or the total imaginary part of the permittivity, the so-called loss factor:

$$p_v = \frac{1}{2}\sigma_{\text{total}} \cdot |\vec{E}|^2 = \frac{1}{2}\omega\varepsilon_0\varepsilon''_{\text{total}} \cdot |\vec{E}|^2 \qquad [10.24]$$

With this result (the dependence on the squared electric field magnitude), it is clear that the power dissipation penetration depth δ_{power} is only half the value of the electric field penetration depth δ_{el}.

10.2.3 Dielectric properties

As mentioned above the permittivity, also called the dielectric constant, describes the interaction of an electric field with non- or low-conducting matter. Starting with the simplest case of a static electric field acting on a material, its reaction will be a polarisation $\vec{P}$. This is due to a displacement of the charge centres or an orientation of dipoles on account of Coulomb forces. In simple and often used models the polarisation is proportional to the electric field, which leads to the constitutive relation for the displacement $\vec{D}$, using the permittivity.

$$\vec{D} = \varepsilon_0(\vec{E} + \vec{P}) = \varepsilon_0(\vec{E} + \chi \cdot \vec{E}) = \varepsilon_0\varepsilon \cdot \vec{E} \qquad [10.6b]$$

When a time dependent electric field is applied, another effect can be observed. Due to the mass and the corresponding inertia of the dipoles to rotate or the charge centres to displace, there will be a difference in phase between the applied field and the resulting polarisation. For time harmonic fields this influence can be taken into account by an imaginary part of the permittivity.

Origin of dielectric losses in food substances

Important for microwave applications of food substances are two types of origins of the polarisation and the corresponding losses into heat: the ion conductivity and the dipole-orientation. These two types are addressed in more detail here; different mechanisms that are more prominent at other frequencies can be found, for example, in Hasted (1973). As already mentioned in the previous section, the ion conductivity can be included into the dielectric loss factor by:

$$\varepsilon''_{\text{total}} = \varepsilon'' + \frac{\sigma}{\varepsilon_0\omega} \qquad [10.17]$$

where the second term is determined by the ion conductivity divided by the circular frequency. The ion conductivity itself is dependent on the ion concentrations n_i, the ion valences z_i and their mobilities μ_i (which are unfortunately only in the first approximation independent of the concentrations):

$$\sigma = \sum_i n_i \cdot z_i \cdot \mu_i \qquad [10.25]$$

The frequency dependence of the effect of dipoles (for example, water) can be described by a relaxation behaviour (Debye-relaxation). Starting from the suggestion that the change of polarisation per unit time is equal to the difference of the instantaneous and the steady state value divided by a typical relaxation time τ, one gets the frequency dependence of the permittivity:

$$\varepsilon'(\omega) = \frac{\varepsilon(0) - 1}{1 + \omega^2\tau^2} + 1$$
$$\varepsilon''(\omega) = \frac{\omega\tau}{1 + \omega^2\tau^2} \cdot \varepsilon(0) \qquad [10.26]$$

For real materials the dielectric behaviour of atomic polarisation at light frequencies has to be taken into account, additionally. The zero-frequency value $\varepsilon(0)$ is predominantly determined by the dipole moment of the molecule and the molecular concentration.

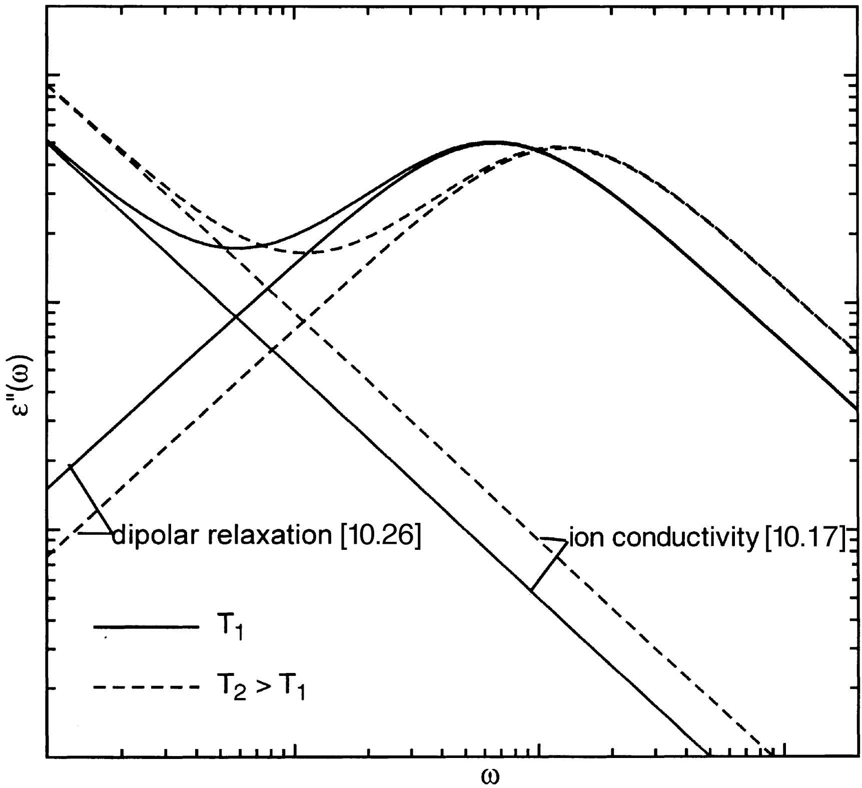


Fig. 10.1 Frequency dependencies of the dielectric loss factor due to dipolar relaxation, ion conductivity and their superposition.

The typical frequency dependence of both important effects on the loss factor can be seen schematically in Fig. 10.1 together with their temperature dependency. This figure shows that the relaxation peak as well as the contribution of the ion conductivity in ε'' are shifted to higher frequency due to the smaller viscosity of the solution and the corresponding higher mobility of ions and dipoles (Feher 1997; Mudgett 1985). For microwave applications the values of the permittivity at 915 MHz and 2.45 GHz are the most interesting ones. Nevertheless, their temperature dependence cannot be predicted without knowing the influences of the temperature dependence on the relaxation frequency, for example. Let us take a look at four examples:

1. *Pure water above the melting point.* Since the relaxation frequency of pure water at 20°C is in the range of 20 GHz, the microwave frequency of 2.45 GHz is smaller than the peak point of ε''. Heating the water will shift the peak to higher frequencies, which will result in a decreasing loss factor value.
2. *Salt solution.* As above, the heating of a salt solution will shift the relaxation peak to higher frequencies yielding a smaller ε'' value; on the other hand,

the higher mobility of the salt ions results in an increased ε''. For a certain temperature and concentration range this could lead to a stable total value of the loss factor.

3. *Ethanol.* The corresponding relaxation frequency peak for ethanol at 10ºC is below 1 GHz. It shifts towards 2.45 GHz at approximately 50ºC yielding an increased ε'' value with temperature in this range. The consequence is an enhanced heating rate with increasing temperature, which can lead to fast overheating of localised spots. This unstable behaviour of a higher ε'' with increasing temperature is called 'thermal runaway' and also occurs for example in cellulose, and should normally be avoided.
4. *Pure water in the melting point range.* A similar effect is observed during the melting of water. When the water is frozen, the dipoles do not have the mobility to rotate with the applied electric field. The corresponding ε'' value is therefore very small (approximately 0.003). As soon as melting occurs, the high molecular mobility yields an ε'' value, which is approximately 3000 times higher than in the frozen state (see Table 10.3). As a consequence an interesting effect to observe is the boiling of water in the presence of water in frozen state, an effect far from equilibrium.

Food material mostly consists of a complex mixture of various ingredients. As already mentioned, water and salts are the most important ingredients, showing the strongest interactions with microwaves. Therefore the dielectric properties are strongly dependent on their concentrations. The interaction of microwaves with components other than ions and dipoles are rather negligible, yielding small values of the permittivity. Nevertheless, only in simple cases of non-interacting mixtures, can model calculations completely describe their dielectric behaviour (Datta *et al.* 1995; Erle *et al.* 2000; Persch 1997). In

Table 10.3 Dielectric properties of various materials at 2.45 GHz. Apart from the case of ice, the values are valid for room temperature. Corresponding to the variation in natural materials the dielectric property values are given in different accuracy here

Material	ε'	ε''	Remarks
Water	78.1	10.4	
Ice	3	0.003	$\vartheta = -2$ºC
1 molar NaCl-solution	74.8	21.4	
2 molar NaCl-solution	65.6	69.1	
Ethanol	7.5	7.1	
10% Ethanol-solution	71.5	13.8	(weight %)
10% Sucrose-solution	74.5	13.1	(weight %)
Vegetable oil	3.1	0.4	
Beef tissue	50	15	(uncooked)
Cooked ham	45	25	
Mashed potatoes	65	21	
Carrot tissue	71	18	(water content 89.7%)
Apple tissue	64	13	(water content 84.0%)

particular, for mixtures of highly interactive molecules, for example different types of dipoles, simple theories predicting permittivities of the mixtures do not succeed. The reason is the existence of molecular clusters of different dipole moments and inertia and therefore a changed relaxation frequency, that lead to completely different dielectric constants.

The consequence is, that often only measured values can act as starting values for accurate calculations. Some measured values of different food substances are shown in Table 10.3; further dielectric properties can be found in the literature (e.g. Mudgett 1985; Bengtsson 1971; Datta *et al.* 1995) or in a www database presenting a collection of physical properties of foods (www.nel.uk/fooddb/).

Measurement of dielectric properties of food in the microwave frequency range
Among many possible methods for the measurement of dielectric properties in the microwave frequency range (Rost 1978), we choose two well-suited and widely spread methods for food material to be presented here: (a) the open-ended coaxial line dielectric probe, and (b) resonator methods.

The open-ended coaxial line dielectric probe
The set-up consists of a network analyser, which is the source and the detector of electromagnetic waves of defined frequency. It is coupled by a coaxial line to an open-ended probe, which has to be in direct contact with the sample to be characterised (a schematic view is shown in Fig. 10.2(a)). The end of the coaxial line, which is defined by the probe itself and the sample, represents a capacity composed of the internal probe capacity and the fringing field capacity. Within this capacity the electromagnetic wave is reflected, whereby the amplitude and the phase of the reflected wave are influenced by the fringing field capacity, which is dependent on the permittivity of the sample material. By changing the frequency of the incident wave, frequency dependent dielectric properties can be measured, and can be used to estimate their temperature dependencies. For homogeneous fluids or samples with flat surfaces, in particular, it is quite simple to use. Disadvantages of the system are that a flat surface of the sample has to be guaranteed to make a direct contact between probe and sample possible. Also the sample should be homogeneous in the sensible depth of the probe, which is in the mm-range, and the values of both the real and the imaginary part of the permittivity must not be very small for good accuracy.

Resonator methods
Resonator methods (Fig. 10.2(b)) consist of a microwave resonator (a metallic cavity), where at certain frequencies (called resonant frequencies) standing waves can exist. In these frequency ranges resonant curves of the microwave cavity change due to a dielectric filling, which can be detected by a network analyser. Generally by inserting a dielectric material the resonant frequency decreases and the width of the resonant curve increases with increasing ε' or ε'', respectively. For special geometries and symmetries (namely the concentric cylindrical geometry) the governing Maxwell's equation can be analytically

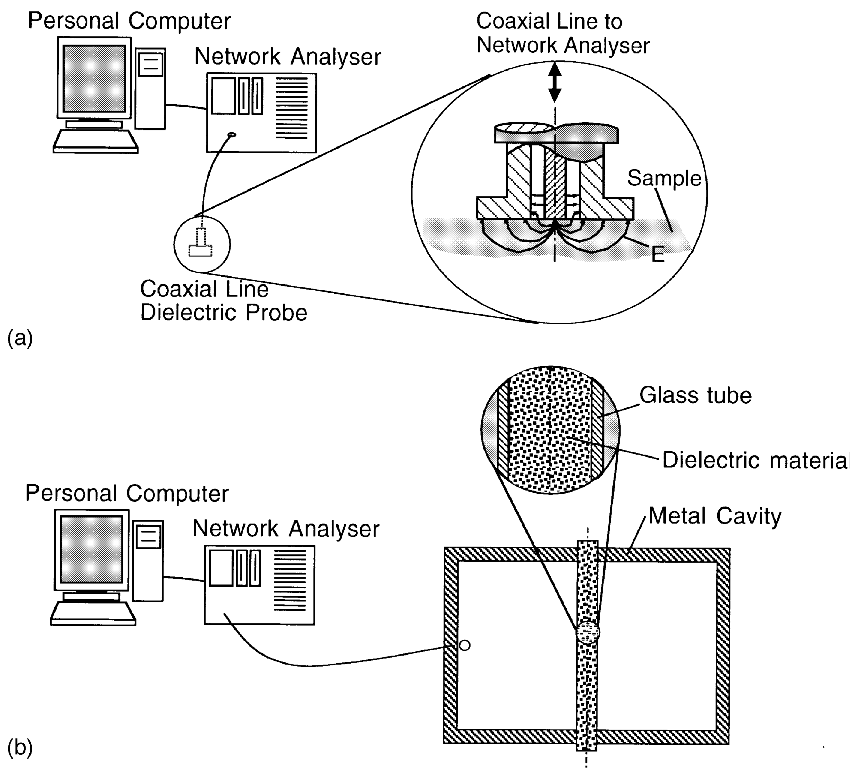


Fig. 10.2 Schematic view of measuring systems for dielectric properties: (a) Open-ended coaxial line dielectric probe. (b) Partially filled resonator system.

solved yielding equations for ε', ε'' (Rost 1978; Regier and Schubert 2000). In other cases calibration procedures that use materials with known dielectric properties and correlate them with measured resonant curve changes, may be used (e.g. Bengtsson 1971).

The most prominent advantage of the resonator methods is their suitability for more heterogeneous material, since they sample a larger volume and average over inhomogeneties. Also both high and low values of permittivities can be measured with high accuracy but with different kinds of resonators (completely or partially filled cavities). The major disadvantage of the resonator methods is that each resonator can only determine the permittivity at its resonant frequencies, which is additionally dependent on the investigated material.

10.2.4 Microwave sources, waveguides and applicators

Magnetrons

By far the microwave source most used for industrial and domestic applications (Metaxas (1996) mentions a figure of 98%) is the magnetron tube. Therefore, we limit our discussion here to the description of a magnetron and only from a phenomenological point of view. More detailed descriptions can be found in, for example, Metaxas and Meredith (1983) and Püschner (1966).

A magnetron is a vacuum tube with a central electron emitting cathode of highly negative potential (see Fig. 10.3), which is surrounded by a structured anode. The anode structure forms cavities, which are coupled by their fringing fields and have the intended microwave resonant frequency. Due to the high electric d.c. field, the emitted electrons are accelerated radially but are deflected by an orthogonal magnetic d.c. field, yielding a spiral motion. If the electric and the magnetic field strength are chosen appropriately, the resonant cavities take energy from the electrons which can be coupled out by a circular loop antenna in one cavity into a waveguide or a coaxial line.

The power output of a magnetron can be controlled by both the tube current and the magnetic field strength. The maximum power is generally limited by the temperature of the anode; practical limits at 2.45 GHz are approximately 1.5 kW and 25 kW for air- or water-cooled anodes, respectively (Roussy and Pearce 1995). Due to their larger size, 915 MHz magnetrons can achieve higher powers per unit. The efficiencies of modern 2.45 GHz magnetrons range at approximately 70% most limited by the magnetic flux of the economic ferrite magnets used (Yokoyama and Yamada 1996), whereas the total efficiency of microwave heating applications often are lower due to unmatched loads.

Waveguides

For guiding an electromagnetic wave, transmission lines (e.g. coaxial lines) and waveguides can be used. At higher frequencies like microwaves, waveguides have lower losses and are therefore used for power applications. Principally, waveguides are hollow conductors of normally constant cross-section, whereby

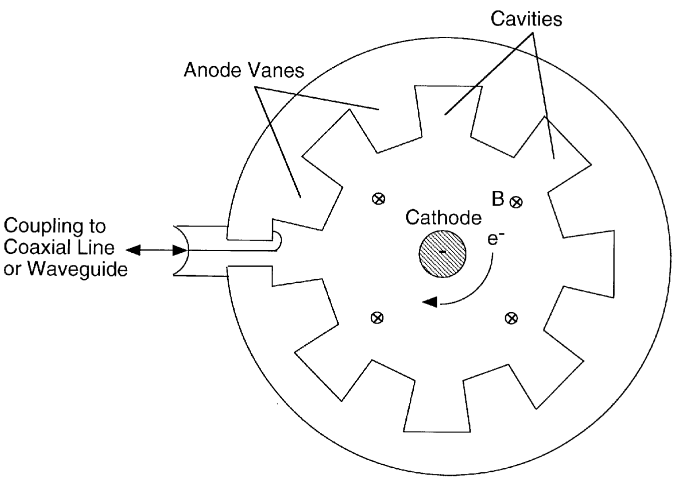


Fig. 10.3 Schematic view of the set-up and the function of a magnetron.

rectangular and circular forms are of most practical use. Its size defines a minimum frequency f_c (the so-called cut-off frequency) by the solution of the wave equations (eq. [10.11] and [10.12]) and appropriate boundary conditions (Table 10.2), below which waves do not propagate. Within the waveguide the wave may spread out in so-called modes, which define the electromagnetic field distribution within the waveguide. These modes can be split into transversal electric (TE) and transversal magnetic (TM) ones, describing the direction of the electric or the magnetic field, respectively, towards the propagation direction. The most commonly used waveguide is of rectangular cross-section with a width equal to double the height in TE10 mode, which is depicted in Fig. 10.4.

Microwave applicators

Already the waveguide can be used as an applicator for microwave heating, when the material to be heated is introduced by wall slots and the waveguide is terminated by a matched load. This configuration is then called a travelling wave device, since the location of the field maxima change with time. A radiation through the slots only occurs if wall current lines are cut and the slots exceed a certain dimension, which can be avoided (Roussy and Pearce 1995). More common in the food industrial and domestic field are standing wave devices described in the next section, where the microwaves irradiate by slot arrays (that cut wall currents) or horn antennas (specially formed open ends) of waveguides.

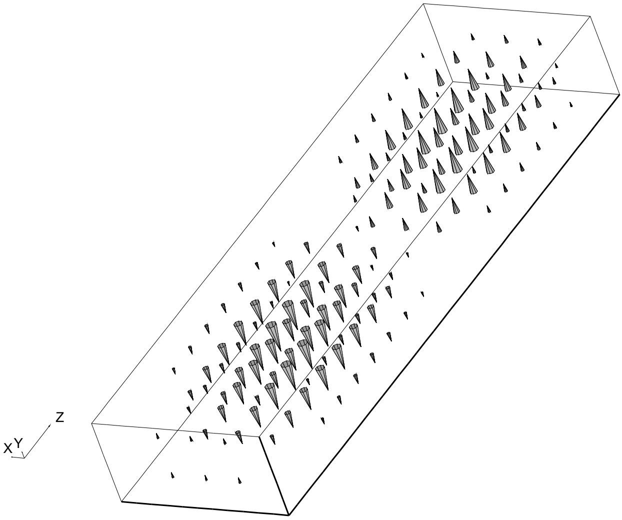
One should distinguish between three types of applicators by the type of field configurations: (a) near field applicators, (b) single-mode applicators, and (c) multi-mode applicators.

Near field applicators

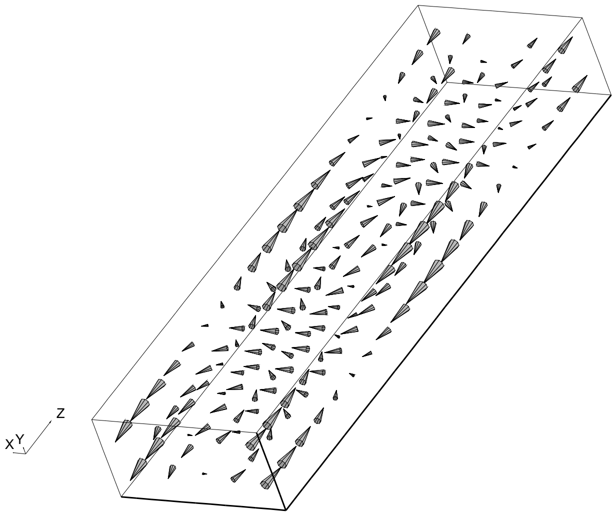
In the case of near field applicators, the microwaves originating from a horn antenna or slot arrays 'hit' directly the product to be heated, and are almost completely absorbed by it. The transmitted microwaves have to be transformed into heat in dielectric loads (usually water) behind the transmitted product. This case is very similar to the travelling wave device, since a standing wave cannot develop. Consequently no standing wave pattern can be formed, which can yield a relatively homogeneous electrical field distribution (depending on the mode irradiated from the waveguide) within a plane orthogonal to the direction of propagation of the wave.

Single-mode applicators

The near field applicators as well as the travelling wave devices work best with materials with high losses. For substances with low dielectric losses, applicators with resonant modes, which enhance the electric field at certain positions, are better suited. The material to be heated should be located at these positions. Single-mode applicators consist generally of a feeding waveguide and a relatively small microwave resonator with dimensions in the range of the wavelength. As in the case of the resonator measurements (Section 10.2.3) a



a.



b.

Fig. 10.4 Electric (a) and magnetic (b) field distribution in a rectangular TE10 waveguide. The arrows point to the actual field direction, their size shows the magnitude of the field amplitudes.

standing wave (resonance) exists within the cavity at a certain frequency. The standing wave yields a defined electric field pattern, which can then be used to heat the product. An example of such a system is shown in Fig. 10.5, where a cylindrical TM010 field configuration, with high electric field strength at the centre, is used to heat a cylindrical product that could be transported through tubes (e.g. liquids).

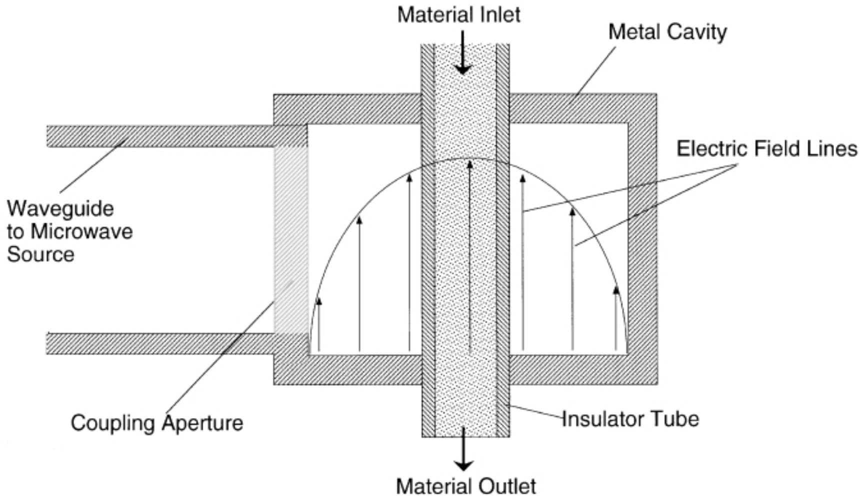


Fig. 10.5 Schematic view of a TM010 resonator, as an example of a single-mode heating device.

The small dimensions of the applicator are needed to avoid different modes from the used one, since the number of modes per frequency range grows very fast with cavity dimensions. It has to be noted that this type of applicator has to be well matched to the load, since the insertion of the dielectric material naturally alters the resonant modes.

Multi-mode applicators
By increasing the dimensions of the cavity a fast transition from the single mode to the multi-mode applicator occurs, due to the fast growth of mode density with applicator size and the fact that microwave generators like magnetrons do not emit a single frequency but rather a frequency band. In industrial and domestic applications the multi-mode applicators play by far the most important role, since most of the conveyor-belt-tunnel applicators and the microwave ovens at home are of the multi-mode type due to their typical dimensions. Despite the high number of stimulated modes, a non-homogeneous field distribution (constant in time) will develop depending on the cavity and the product geometry and the dielectric properties of the material to be processed. In opposition to the case of the single mode application, normally this inhomogeneous field distribution, which would result in an inhomogeneous heating pattern is not desired. Possible remedies are either moving the product (conveyor belt, turn table) or changing the field configuration by varying cavity geometries (e.g. mode stirrer), which are explained in more detail in the corresponding application sections.

10.3 Microwave applications

A detailed and more extensive description of many microwave uses in the food sector can be found in the monograph by Decareau (1985). Here only the main purposes are outlined together with some examples, that illustrate the large spectrum of different applications with the various demands.

10.3.1 Household ovens and product engineering

The principal set-up of a household microwave oven consists of a magnetron tube, which is coupled by a waveguide and an aperture to a commonly rectangular cavity. Due to reflections a standing wave develops, which leads to an inhomogeneous heating pattern even in a homogeneous sample. Three possible remedies can effectively reduce this undesirable heating behaviour. The simplest method is to use low microwave power mostly achieved by pulsing the microwave irradiation. The consequence is, that the relatively slow heat conduction mechanism levels the temperature gradients within the product. Another often used system is the turntable of microwave ovens. The movement of the dielectric material enhances the power uniformity in two ways: by averaging different electric field strength areas and by changing the electric field pattern due to the varied geometrical set-up, which yields different field configurations. Concurrent to this turntable, mode stirrers can be used, which are placed just before the aperture of the waveguide to the cavity. This mode stirrer also changes the geometrical set-up of the complete cavity and therefore yields time dependent field configurations, leading to more even product heating. In most cases these methods have to be combined to get sufficient results.

Another way to get a more uniform or a desired temperature distribution is to change product properties (e.g. the ingredients, the geometrical set-up of the product, the packaging, etc.), instead of the processing (microwave heating) method. This way of product enhancement is called product engineering or product formulation. In the literature and in various patents possible approaches have been developed; a detailed overview is presented in Decareau (1992). Here only some illustrative examples are described.

In order to get similar heating rates and temperatures in products with different dielectric or thermodynamic properties, containers covered by a metal foil with appropriate apertures have been proposed. A different approach is changing the location of different foods on the plate. Alternatively, the incorporation of susceptors into the packaging is possible. These susceptors consist of material with high losses; consequently they can reach high temperatures which they can transfer to the desired location by irradiation or conduction. With these materials even surface browning is possible in microwave ovens, which is normally prevented by too low surface temperatures due to evaporation.

The browning and crisping effects are also the objective of combination ovens, which mostly use an additional conventional (resistive) heating equipment within the microwave oven. Recently, a method called jet impingement, where very hot (up to 500ºC) and very fast air jets flow contrary to the primary microwave ‘fronts’, is introduced in the microwave market. The resulting problem of complicated cooking power programs should be overcome with Internet access, where these recipes can be downloaded directly to the oven (Franke and Pool 2000).

10.3.2 Industrial ovens

Industrial applications mostly need continuous processing due to the desired high throughputs. Therefore continuous microwave applicators had to be developed, starting in 1952 with the first conveyor belt oven patent (Spencer 1952). Nevertheless, due to the lack of high power microwave generators the start of its industrial use was nearly ten years later. Today’s industrial ovens (a more complete overview can be found in Decareau (1985)) may be differentiated into two groups by the number and power of microwave sources: high power single magnetron and low power multi-magnetron devices. Whereas for a single mode unit only a single source is possible, in all other systems (multi-mode, near field or travelling wave system) the microwave energy can be irradiated by one high power magnetron or several low power magnetrons.

An important hurdle for all continuous ovens is the avoiding of leakage radiation through the product in- and outlet. The leakage radiation is limited by law to 5 mW/cm^2 at any accessible place. For fluids or granular products with small dimensions (cm-range), this value can be guaranteed by in- and outlet sizes together with the absorption in the entering product, sometimes with additional dielectric loads just in front of the openings. Especially in the case of larger product pieces, inlet and outlet gates, which completely close the microwave application device, have to be used. A conveyor belt oven with its alternative power sources and openings is shown schematically in Fig. 10.6.

10.3.3 Industrial processes

In industry a variety of microwave applications have been and are still used. For a more complete survey, illustrating many real commercial processes, see Decareau (1985), Metaxas and Meredith (1983), Metaxas (1996), Roussy and Pearce (1995), Buffler (1993) and various authors (1986).

The use of microwave energy in food processing can be classified into six unit operations: (re)heating, baking and (pre)cooking, tempering, blanching, pasteurisation and sterilisation, and dehydration. Although their objectives differ, these aims are established by similar means: an increase in temperature. Nevertheless, for each special use (different from pure microwave heating), different advantages and disadvantages have to be taken into account. These are presented in the next sections together with some examples of real industrial applications.

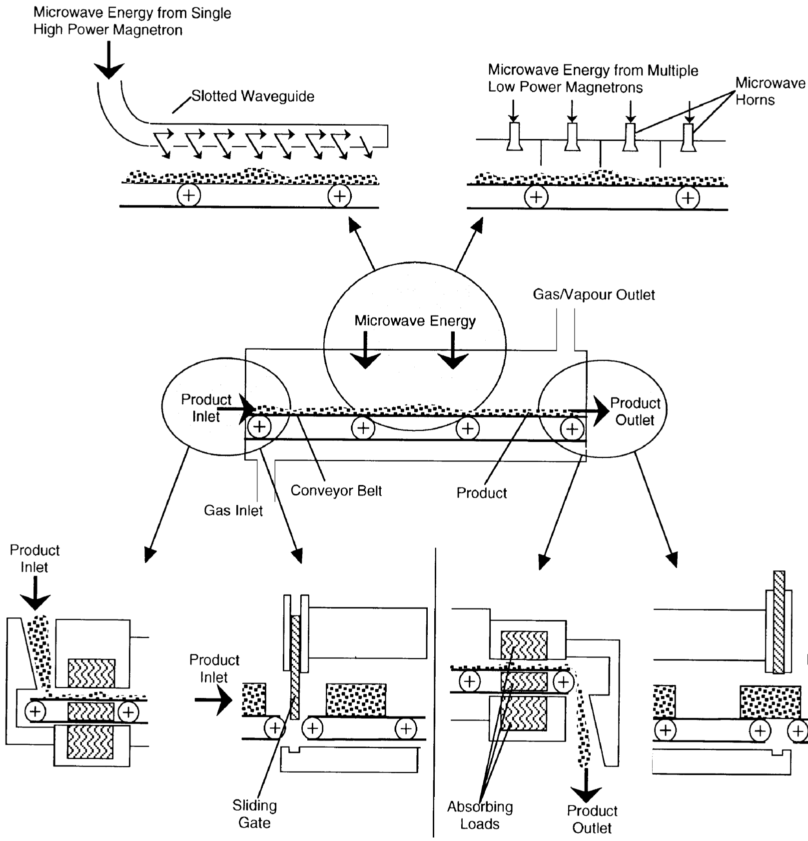


Fig. 10.6 Schematic view of a continuous conveyor belt microwave tunnel, with alternative microwave energy inlets (above) and various product in- and outlets (at bottom).

Baking and cooking

In the process of baking bread, cakes, pastry, etc., microwaves have been used and studied by several authors; references can be found in Rosenberg and Bögl (1987a). The major task of the microwaves is to accelerate the baking, leading to an enhanced throughput with negligible additional space required for microwave power generators. Often combined with conventional or infrared surface baking, microwave use avoids the remedy of lack of crust formation and surface browning. With the fast combined process also different flour can be used with high α-amylase and low protein content (for example from European soft wheat). In contrast to conventional baking the microwave heating inactivates this enzyme fast enough (due to a fast and uniform temperature rise in the whole product) to prevent the starch from extensive breakdown, and develops sufficient CO_2 and steam to produce a high porous good (Decareau 1986).

One difficulty in the microwave baking process was to find a microwavable baking pan, that is sufficiently heat resistant and not too expensive for commercial use. But already by 1981 and 1982 patents were issued overcoming this problem using metal baking pans in microwave ovens (Schiffmann *et al.* 1981, Schiffmann 1982).

Today, the main use of microwaves in the baking industry is microwave finishing. While the conventional oven technique is used at the beginning with high moisture dough, microwaves improve the end baking, where the low heat conductivity would lead to considerably higher baking times.

Microwaves can also be applied as part of a parallel process. One example is the frying of donuts with microwave assistance (Schiffmann 1986), resulting in a shorter frying time and a lower fat uptake. Also the (pre)cooking process can be accelerated with the help of microwaves, as has been established for (pre)cooking of poultry (Decareau 1986), meat patty and bacon. A convective air flow removes the surface water using microwaves as the main energy source, thus rendering the fat and coagulating the proteins by an increased temperature. Also this process yields a valuable by-product namely rendered fat of high quality, which is used as food flavorant (Schiffmann 1986).

Tempering

Another widely used industrial microwave application is the tempering of foods (Metaxas (1996) mentions a figure of 250 units all over the world). Tempering is defined as the thermal treatment of frozen foods to raise the temperature from below −18ºC to temperatures just below the melting point of ice (approximately −2ºC). At these temperatures the mechanical product properties are better suited for further machining operations (e.g. cutting or milling).

The time for conventional tempering strongly depends on the low thermal conductivity of the frozen product and can be in the order of days for larger food pieces such as blocks of butter, fish, fruits or meat. Due to the long time, the conventional process needs large storage rooms, there is a not-negligible drip loss and the danger of microbial growth. By using microwaves (mostly with 915 MHz due to their larger penetration depth) the tempering time can be reduced to minutes or hours (Edgar 1986) and the required space is diminished to one sixth of the conventional system (Metaxas 1996). Another advantage is the possibility to use the microwaves at low air temperatures, thus reducing or even stopping microbial growth.

Of very high importance is the heating uniformity and the control of the end temperature to avoid localised melting, which would be coupled to a thermal runaway effect. The best homogeneity in this application is reached in a multi-source multi-mode cavity, equipped with mode stirrers (Metaxas 1996).

Drying

The main cause for the application of microwaves in drying is the acceleration of the processes, which are (without using microwaves) limited by low thermal conductivities, especially in products of low moisture content. Correspondingly sensory and nutritional damage caused by long drying times or high surface temperatures can be prevented. Another advantage is the possible avoidance of case hardening, due to a more homogeneous drying, without large moisture gradients.

Generally, microwave drying can be subdivided into two cases, the drying at atmospheric pressure and that with applied vacuum conditions. Until now, more common in the food industry are combined microwave-air-dryers, that could again be classified into a serial or a parallel combination of both methods. In the serial process, mostly the microwaves are used to finish partly dried food or food of low moisture content, where an intrinsic levelling effect is advantageous: the loss factor is often dominated by the water concentration, therefore the places of high water content transform more of the microwave energy into heat and are selectively dried. Well studied and still applied examples for a serial hot air and microwave dehydration are pasta drying (Decareau 1985) and the production of dried onions (Metaxas and Meredith 1983).

Intermittently successful in the 1960s and 1970s was the finish drying of potato chips, but the process did not survive due to microwave-intrinsic and extrinsic reasons (O'Meara 1977).

The combination of microwave and vacuum drying also has a certain potential. Though the microwave assisted freeze drying is well studied, as can be read in detail in Sunderland (1980), up to now practically no commercial industrial application can be found, due to high costs and a small market for freeze dried food products (Knutson *et al.* 1987).

It seems that microwave vacuum drying with pressures above the triple point of water has more commercial potential. Clearly, the benefit of using microwave energy is overcoming the disadvantage of very high heat transfer and conduction resistances, leading to higher drying rates. These high drying rates correspond also to the retention of water insoluble aromas (Erle 2000) and to less shrinkage. The use of vacuum pressures is very favourable for high quality food substances, since the reduced pressure limits the product temperatures to lower values, as long as a certain amount of free water is present. This enables the retention of temperature sensitive substances like vitamins, colours, etc. Commercial applications of microwave vacuum dehydration are the concentration or even powder production of fruit juices and drying of grains in short times without germination (Decareau 1985).

A relatively new and successful combination of pre-air-intermittent microwave vacuum (called puffing) and post-air-drying is predominantly used to produce dried fruits and vegetables, with improved rehydration properties (Räuber 1998). By the conventional pre-drying due to case hardening the form can be stabilised, the microwave vacuum process opens the cell structures (puffing) due to the fast vaporisation and an open pore structure is generated. The consecutive post-drying reduces the water content to the required moisture.

Pasteurisation and sterilisation

Since microwave energy can heat many foods (containing water or salts) effectively and fast, its use for pasteurisation and sterilisation has also been intensively studied. Many references can be found in the review by Rosenberg and Bögl (1987b).

In early work, beside the thermal heating effect on microorganisms also non-thermal effects seemed to be found. Physically a non-thermal effect on molecules is very improbable, as becomes clear when the quantum energy of photons of microwaves, of a thermal radiator and the energy of molecular bonds are compared. The quantum energy of a photon of $f = 2.45\,\mathrm{GHz}$ is defined by $E = hf \approx 1 * 10^{-5}\mathrm{eV}$, the typical energy of a photon radiated from a body of 25ºC ≈ 298K equals $E = kT \approx 0.26\,\mathrm{eV}$ and the energy of molecule bonds are in the eV range. Since the collection of energy with time for bound electrons is forbidden by quantum mechanics, only multi-photon processes, which are very unlikely, could yield chemical changes. More likely is the induction of voltages and currents within living cell material, where eventual consequences are still in discussion (Sienkiewicz 1998). From the practical point of view, the non-thermal effects, found in early work could either not be reproduced or could be explained later by the influence of inhomogeneous temperature distributions.

No longer in doubt are the thermal effects of microwaves, which can be used for pasteurisation and sterilisation. Academic and industrial approaches to microwave pasteurisation or sterilisation cover the application for prepacked food like yogurt or pouch-packed meals as well as the continuous pasteurisation of fluids like milk (Decareau 1985; Rosenberg and Bögl 1987b). For the packed food systems, conveyor belt systems were intended (e.g. Harlfinger 1992). For continuous fluid pasteurisation or sterilisation tubes intersecting waveguides or small resonators were developed (Sale 1976).

Whereas the pasteurisation process can take place at atmospheric pressures, in the case of sterilisation only temperatures of more than 100ºC may be used, in order to achieve satisfactory short sterilisation times and to maintain high product quality. For products which contain free water, like many food products, the reachable temperature at atmospheric pressure is limited to the boiling point at around 100ºC. Therefore, the pressure during the sterilisation process has to be increased to overpressure values. The consequence is the need for special compression and decompressing systems, e.g. sliding gates, that have to be connected to the microwave heater.

Advantages of using microwaves in microorganism deactivation are the possibly high and homogeneous heating rates, also in solid foods (heat generation within the food) and the corresponding short process times, which can yield a very high quality. For both processes it is extraordinarily important to know or even to control the lowest temperatures within the product, where the microoganism destruction has the slowest rate. Since both calculation and measurement of temperature distributions are still very difficult (see Section 10.4), this is one reason that up to now microwave pasteurisation and sterilisation can be found very seldom in industrial use, and then only for batch sterilisation operations.

10.4 Modelling and verification

In the beginning of microwave processing the product and process development was essentially a trial-and-error procedure. Due to the lack of powerful computers it was nearly impossible to calculate realistic temperature or even electromagnetic field distributions within microwave applicators when products were present. The reason for this is the number of coupled partial differential equations, describing the physical problems of electromagnetism, heat and mass transfer, which have to be solved in a parallel manner.

Meanwhile for the separated problems, numerical software packages are available and there is also progress in the solution of the coupled problem, which best describes real processes. The governing equations of electromagnetism, Maxwell's equations, have already been described in Section 10.2.2, together with the wave solutions for the simple one-dimensional plane wave example. The resultant exponentially damped wave within a material with dielectric losses have also often been used for the three-dimensional case, in order to simply estimate the power distribution within products. More sophisticated approaches calculating more realistic solutions are presented later in this chapter, but first the governing equations for heat and mass transfer and the coupling to electromagnetism are introduced.

Starting from the continuity equation, the thermal energy equation and Fick's law, a general equation for heat transfer can be described by:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \cdot \nabla T) = -\nabla \cdot q_R - \sum_i h_i I_i + Q_{em} \qquad [10.26a]$$

While the left side of this equation is well known from the traditional heat conduction equation, the terms on the right side have to be added for heat transfer by radiation and by a mass sink or source (e.g. phase change of water or due to diffusion or convection) and for the heat source by the dielectric losses, respectively (Metaxas 1996). If the product consists of a solid but moist material, the radiative term has only to be taken into account at surfaces to gaseous materials yielding additional boundary conditions and the mass sink and source can be replaced by the moisture content changing:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \cdot \nabla T) = \varepsilon_v \rho h_{evap} \frac{\partial M}{\partial t} + Q_{em} \qquad [10.26b]$$

Especially for the case of drying, this equation is coupled to the mass transfer equation, here written for the moisture content M:

$$\frac{\partial M}{\partial t} = \nabla \cdot (\alpha_M [\nabla M + \delta_T \nabla T + \delta_p \nabla p]) \qquad [10.27]$$

This equation becomes even more difficult when a product porosity has to be taken into account with its capillary forces and the possible shrinkage. The equation describing the behaviour of the total pressure can also be found in Metaxas (1996):

$$\frac{\partial p}{\partial t} = \alpha_p \Delta p - \frac{\varepsilon_v}{c_a} \frac{\partial M_l}{\partial t}. \qquad [10.28]$$

The above equations and the electromagnetic equations are coupled in two ways: explicitly by the values of the temperature, the moisture content, the pressure and the electromagnetic heat generation (eq. [10.24]), but also implicitly by the temperature and moisture dependency of the material properties. In general, these material properties also have a directional dependency, which has to be expressed by tensor properties. This is especially valid for inhomogeneous natural material; as a well known example the variation of mass transfer coefficient along and orthogonal to the predominant fibre orientation can be mentioned. Additionally these equations are already simplified by the assumption that there would be no volume change of the solid material structure. Indeed volume shrinkage can often be observed during heating and especially drying. At the product surface, boundary conditions come into operation to take into account the external heat, mass and pressure transfer, respectively.

Although there is a fast development of numerical calculation power, a complete calculation could not be done without some simplifications, up to now. These simplifications have to be established, neglecting some of the above-mentioned dependencies. For the case of pure electromagnetics, commercial numerical software packages are available (a comparison of their potential for microwave heating is addressed by Yakovlev (2000), but is not yet finished), but also some home-built software codes are described in the literature. Most of them originate from the telecommunications area and are not perfectly suited for microwave heating applications, with their special demands. General to all numerical techniques is the discretisation of the partial differential equations or their corresponding integral equations together with the suitable boundary conditions on a calculation grid. In practical use most common are the method of finite differences in time domain (FDTD), the finite integration method (FIM), the finite element method (FEM), the method of moments (MOM) and the transmission line matrix method (TLM), and also methods using optical raytracing codes. Again, we have to refer to special publications (Metaxas 1996; Lorenson 1990), for a more detailed overview. Some approaches are mentioned here, together with the articles, where the interested reader can find more information.

For short times and high microwave power densities, the heat transfer, which is in this case much slower than the microwave heat generation itself, can be neglected. While the one-dimensional example has already been addressed analytically in Section 10.2.2, which has educational value, of course, for more realistic problems two or three dimensions are needed. The temperature rise in a defined volume is then directly proportional to the microwave heat generation rate, which can be inferred from the effective electric field value and the dielectric loss factor (eq. [10.24]). Relatively new results using this approximation can be found for example in Fu and Metaxas (1994), Liu *et al.* (1994), Sundberg *et al.* (1998), Dibben and Metaxas (1994) and Zhao and Turner (1997).

In only a few papers is electromagnetism already coupled to a thermal model; examples including heat conduction can be found in Torres and Jecko (1997) and Ma *et al.* (1995). In Haala and Wiesbeck (2000) additional to heat conduction, heat transport by radiation is addressed by a raytracing algorithm. Since for most food applications the temperatures are more moderate in comparison to ceramics sintering, where the latter software code originates, this radiation seems to be more negligible than heat transport by convection or evaporation. While in a recent publication (Zhang and Datta 2000) the heat transfer from the product surface by free convection in a microwave oven is addressed by the corresponding boundary condition, both ways of heat and mass transport within the product are taken into account only in more phenomenological studies: either the microwave heating phenomenon is simplified by using Lambert's or Mie's equations for special geometries (Lian *et al.* 1997; Jun *et al.* 1999), or the heat and mass transport is modelled by the use of non-local balances (Roques and Zagrouba 1997; Erle 2000; Zhou *et al.* 1995).

Generally, it has to be concluded that the published model calculations are limited mostly to special cases or to very similar ones, where they have been applied successfully. Therefore, after model calculations their verification is also a very important task, and in the case of microwave applications this is not at all simple. The electromagnetic fields are not easily measurable without changing them by the measurement procedure itself. The same has to be said for the measurement of temperature distributions. A relatively old bibliography of different temperature indication methods in microwave ovens can be found in Ringle and Donaldson (1975). Without enormous efforts normal thermocouples could not be used in microwave devices, since their metallic wires at least change the field distribution. Moreover only a poor local resolution would be achievable. While the first problem can be overcome by fibre optic thermometers, the reachable local resolution is often not sufficient, either. Besides, the fibre optic sensors are rather delicate and expensive in comparison to conventional thermocouples.

A different approach to determine temperature distributions in microwave devices is the use of model substances that change their properties when a certain temperature is reached. One published method uses the colour change of the model substance (Risman *et al.* 1993), another one a coagulation effect (Wilhelm and Satterlee 1971). Care has to be taken to match the other important properties of the model to the real product (e.g. the dielectric and thermal properties). In order to determine surface temperatures, infrared photographs and also liquid crystal foils (Grünewald and Rudolf 1981) or thermofax paper (Feher 1997) are established methods. By the development of solid phantom foods that can be taken apart practically instantly along pre-cut planes, this disadvantage could be weakened.

All the above-mentioned methods can give useful hints of the temperature distribution, but cannot really prove the calculated temperature values within the product. For this task nowadays the sophisticated method of nuclear magnetic resonance imaging can be used, that can measure three-dimensional temperature distributions without destruction of the product (Nott *et al.* 1999). The disadvantages of this technique are its huge costs and that inline measurements in an industrial scale process are up to now practically impossible.

10.5 Summary and outlook

Microwave ovens are commonplace in households and are established there as devices of everyday use. Their primary function is still the reheating of previously cooked or prepared meals. The relatively new combination of microwaves with other (e.g. conventional, infrared or air jet) heating systems should enhance their potential for a complete cooking device, that could replace conventional ovens.

Unfortunately, in industry the distribution of microwave processes is still far away from such high numbers. Only a relatively low number of microwave applications can be found in actual industrial production, compared with their indisputable high potential. These successful microwave applications range over a great spectrum of all thermal food processes. The most prominent advantages of microwave heating are the reachable acceleration and time savings and the possible volume instead of surface heating. Reasons mentioned for the failure of industrial microwave applications range from high energy costs, which have to be counterbalanced by higher product qualities, over the conservatism of the food industry and relatively low research budgets, to the lack of microwave engineering knowledge and of complete microwave heating models and their calculation facilities. The latter disadvantage has been partly overcome by the exponentially growing calculating power which makes it possible to compute more and more realistic models by numerical methods. Very important for the task of realistic calculations is the determination of dielectric properties of food substances by experiments and theoretical approaches. Nevertheless in order to estimate results of microwave heating applications and to check roughly the numerical results, knowledge of simple solutions of the one-dimensional wave propagation like the exponentially damped wave is of practical (and also educational) relevance.

But still the best test for numerical calculations are experiments, which yield the real temperature distributions within the product, which is really important especially in pasteurisation and sterilisation applications. While more conventional temperature probe systems, like fibre optic probes, liquid crystal foils or infrared photographs only give a kind of incomplete information about the temperature distribution within the whole sample, probably magnetic resonance imaging has the potential to give very useful information about the heating patterns. Hopefully, this together with the enormous calculation and modelling power will give the microwave technique an additional boost to become more widespread in industrial food production.

The breakthrough of microwave technology in the food industry due to its high potential has been predicted many times before, but it has been delayed every time up to now. That is why we are cautious in predicting the future of microwaves in industrial use. However, we think that the potential of microwave technology in the food industry is far from being exhausted.

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