Microwave heating

The principles of microwave heating as applied to industrial processing are outlined and the basic design of applicators for material processing is described. Industrial applications range from food tempering to rubber vulcanisation and from vacuum drying to sintering of ceramics. Established applications to date are summarised.

By A.C. Metaxas

Microwave heating is a process within a family of electroheat techniques, such as induction, radio frequency, direct resistance or infra-red heating, all of which utilise specific parts of the electromagnetic spectrum. These processes supplement, and in specific cases totally replace, conventional heating or drying systems used in industry. This is because some conventional systems are very bulky, not easy to operate, can pollute the environment due to harmful omissions and above all can be very inefficient.

The major advantages of using microwaves for industrial processing are rapid heat transfer, volumetric and selective heating, compactness of equipment, speed of switching on and off and pollution-free environment as there are no products of combustion. Microwave leakage can certainly be kept well below government recommended levels.

Fundamentals of microwave heating

Dielectric loss

It has long been established that a dielectric material can be processed with energy in the form of high-frequency electromagnetic waves. There are many distinct frequency bands which have been allocated for industrial, scientific and medical (ISM) use, as shown in Table 1, with the principal frequencies centred at 896 MHz (915 MHz in the USA) and 2450 MHz for which equipment can be readily purchased.

In this frequency regime there are primarily two physical mechanisms through which energy can be transferred to a non-metallic material. At the lower microwave frequencies conductive currents flowing within the material due to the movement of ionic constituents, such as salts for example, can transfer energy from the microwave field to the material. This loss mechanism is characterised by an equivalent dielectric conductivity term σ, giving effectively a loss parameter of $\sigma/\omega\varepsilon_o$.

At the other end of the microwave heating spectrum, around 3000 MHz, the energy absorption is primarily due to the existence of permanent dipole molecules which tend to re-orientate under the influence of a microwave electric field, as shown in the inset of Fig. 1. This re-orientation loss mechanism originates from the inability of the polarisation to follow extremely rapid reversals of the electric field. At such high frequencies therefore the resulting polarisation phasor lags the applied electric field. This ensures that the resulting current density has a component in phase with the field, and therefore power is dissipated in the dielectric material.

Table 1 Frequency allocation for industrial, medical and scientific (ISM) purposes in the range 433.92 MHz to 40 GHz

Frequency MHz	**Frequency** tolerance + or -	**Area permitted**
433.92	0-2%	Austria, The Netherlands, Portugal, West Germany, Switzerland
896	**10 MHz**	**UK**
915	**13 MHz**	**North and South America**
2375	50 MHz	Albania, Bulgaria, Hungary, Romania Czechoslovakia, USSR
2450	**50 MHz**	**worldwide except where 2375 MHz is used**
3390	0-6%	The Netherlands
5800	75 MHz	worldwide
6780	0-6%	The Netherlands
24150	125 MHz	worldwide
40680		UK

Source adapted from Ref. 2

The loss mechanism is characterised by the relative loss factor term ε″, which is part of the complex relative permittivity, whereas absolute permittivity is given by $\varepsilon = \varepsilon_o\varepsilon^*$. The two components of the complex relative permittivity shown plotted as a function of the frequency in Fig. 1, for a dipolar liquid or for a wet dielectric, where the losses at microwave frequencies are due to re-orientation polarisation. The conductivity effects of ionic species, shown by the light blue response, dominate at radio frequencies, while the combined loss is shown by the red response.

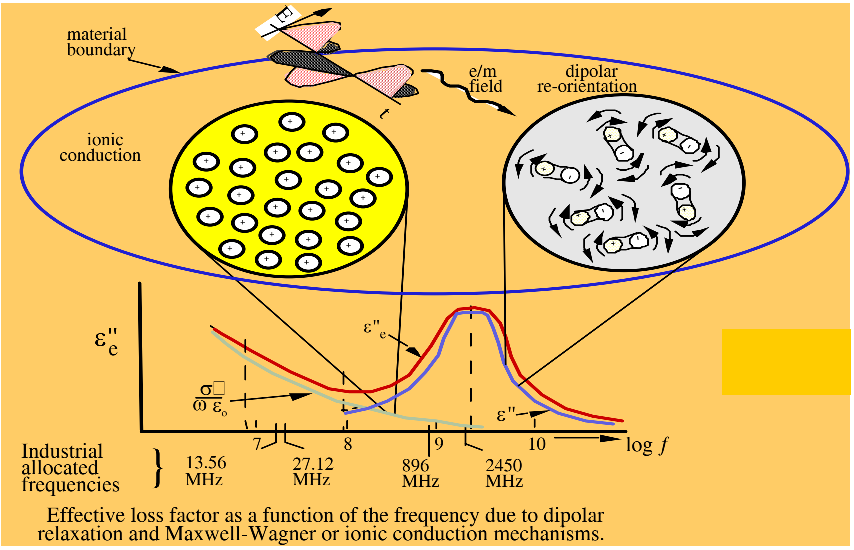


Fig. 1. Effective loss factor as a function of the frequency. The inserts show the dipolar re-orientation and conductive loss mechanisms

Wave equation

The basic equations in microwave heating, through which a number of fundamental parameters are derived, are the total current density established in the dielectric material and the modified wave equation[1]. The total current density includes the contributions of conductive and displacement current densities and is given by the curl of the magnetic field phasor, ***H***:

$$\nabla \times \boldsymbol{H} = \sigma\boldsymbol{E} + \partial\boldsymbol{D}/\partial t \qquad [1]$$

where the first term on the right hand side of eqn [1] is the conductive contribution due to ionic constituents and the second term is due to the displacement current density, where $\boldsymbol{D} = \varepsilon\boldsymbol{E}$, where ***E*** being the applied electric field phasor. The analysis proceeds by considering eqn [1] together with Faraday's equation

$$\nabla \times \boldsymbol{E} = -\,\partial\boldsymbol{B}/\partial t \qquad [2]$$

to derive a differential equation in ***E*** or ***H***. Using the inter-relationship between ***E***, $\partial\boldsymbol{E}/\partial t$ *and* $\partial^2\boldsymbol{E}/\partial t^2$, and assuming that $E = \mathrm{Re}Ee^{j\omega t}$, the following modified wave equation is derived for a dielectric slab where the induced electric field is predominantly constant in the *z*-direction and the magnetic field lies in the *x* -direction:

$$\partial^2 E_z/\partial y^2 = -\,\mu\varepsilon_o K\omega^2 E_z = \gamma^2 E_z \qquad [3]$$

The propagation constant γ is given by

$$\gamma = j\omega\sqrt{K\varepsilon_o\mu} = \alpha + j\beta \qquad [4]$$

where α and β are the attenuation and phase constant, respectively, and the parameter *K* is given be $K = \varepsilon' - j(\varepsilon'' + \sigma/\omega\varepsilon_o) = (\varepsilon' - j\varepsilon_e'')$, where ε_e'' is the effective loss factor shown in red in Fig. 1.

Semi-infinite slab analysis: The simplest case to consider is a horn applicator emanating microwave energy to a relatively thin semi-infinite dielectric slab of high dielectric loss factor as shown in Fig. 2a. The electric field within the dielectric is substantially constant along the *x*-

direction and it decays in the *y*-direction as it traverses the material as depicted in Fig. 2b. Solution of eqn.[3], including time variations and assuming that when $y \to \infty$, E_z must be finite, yields

$$E_z = \mathrm{Re}\ E_o e^{-\gamma y} e^{j\omega t} = E_o e^{-\alpha y} \cos(\omega t - by) \qquad [5]$$

where E_o is the maximum value of the electric field intensity at the material/air interface. Such a simplistic approach to the problem, resulting in an exponential decay, does also have some

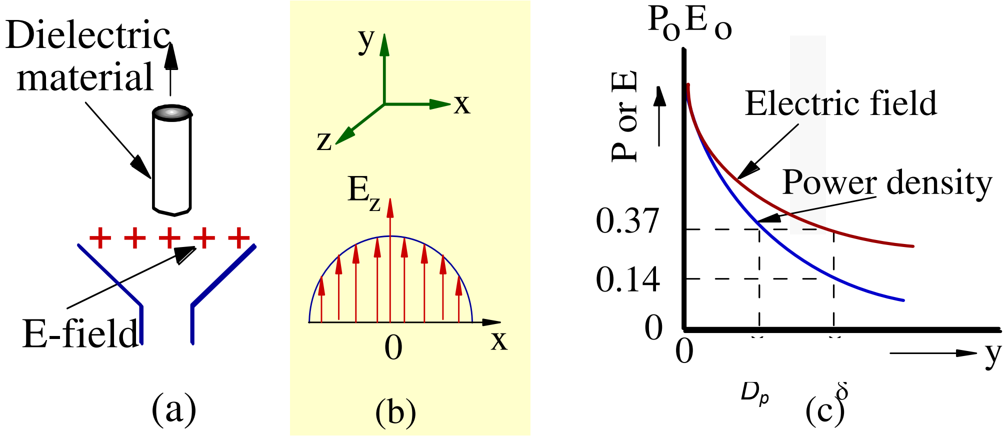


Fig. 2(a) Semi-infinite slab analysis (b) the direction of the E-field along the waveguide face and (c) the electric field and power density distribution

relevance in practice as it relates approximately to the treatment of foodstuffs with microwaves. This is because most foodstuffs have a relatively high effective loss factor ε_e'', which results in a rapidly decaying electric field and justifying the assumption made above which is inherent in the derivation of eqn.[5] Whether a finite slab or a semi-finite slab is considered, the electric field has decayed to a very small value within a very short distance of the air/dielectric interface.

Finite slab: Unless the dielectric properties of the processed material are very high, the assumptions made in the previous paragraph do not hold for a finite slab and the electric field is given by the general solution of eqn. 3:

$$E_z = \mathrm{Re}\ \{[Ae^{-\gamma y} + Be^{+\gamma y}]e^{j\omega t}\} \qquad [6]$$

where *A* and *B* are constants that fit the appropriate boundary conditions. It is not justifiable now to set *B* = O in this case because the slab has medium to low loss factor value and the second term may be of the same order as the first term in eqn.[6]. The electric field in this case does not decay exponentially and more elaborate solutions ought to be found when *y* is set equal to the slab width.

Heating in the standing wave electric field: The analysis of the semi-infinite slab has been applied to a dielectric material placed inside a multimode oven applicator for approximate calculations of the electric field and other parameters. This is justified only if the dielectric loss factor is fairly high, as is the case with most foodstuffs, resulting in a rapidly decaying field. With a medium to low loss dielectric the electric field no longer decays exponentially and more rigorous methods of calculation should be deployed.

Power dissipation within the dielectric

It is often required to estimate the amount of power that can safely be dissipated in a dielectric given that the effective loss factor is known. This can be obtained from considering the Poynting vector ***ExH***, which leads to the following expression for the power dissipated per unit volume[2]:

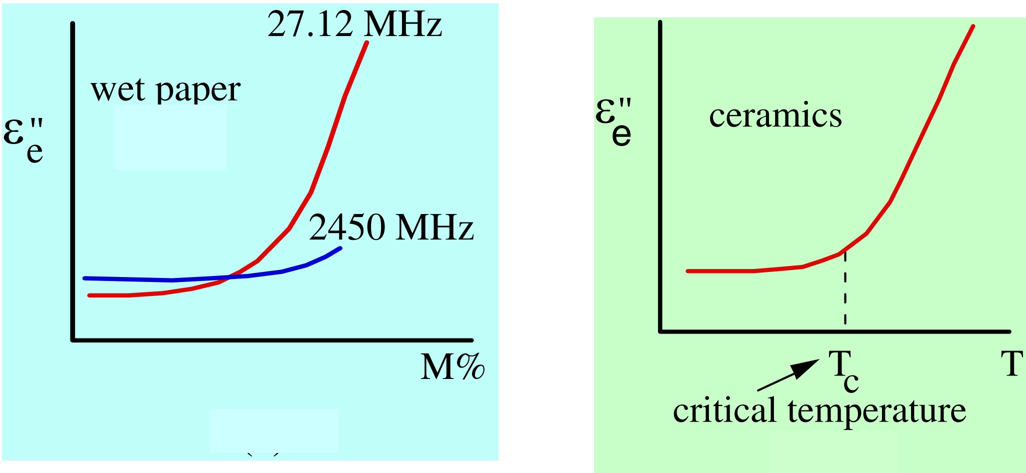
$$Pv = (1/2)[\sigma + \omega\varepsilon_o\varepsilon'']|E_z|^2 = (1/2)\sigma_e|E_z|^2 \qquad [7]$$

where $\omega = 2\pi f$, with *f* being the applied frequency in Hz, σ_e the effective dielectric conductivity and E_z being given by the appropriate expressions above. The total power dissipated *P* in a volume *V* is obtained by integration, therefore

$P = \int_V p_v dV$ [8]

In a multimode cavity applicator fitted with distributed energy sources and mode stirrers, the electric field may be assumed to have been randomised to an approximately constant value, resulting in a volumetric power density $p_V = \sigma_e E_{RMS}^2$, *where* E_{RMS} is the RMS value of the electric field established in the processing zone. For example, for a power dissipation of 10^7 W/m^3 and $\varepsilon_e'' = 0.1$, the required electric field at 2450 MHz is 27 kV/m.

The effective loss factor varies as a function of the moisture content and temperature. Such data, typically shown in Fig. 3, are very useful when assessing the type of applicator and frequency of operation for drying or for other heating applications. For example, the response at a frequency of 27.12 MHz is more suitable for moisture levelling than that at 2450 MHz*,* while the ε_e'' against T response, typically of a high-temperature ceramic material, shows that there is a high probability of thermal runaway above some critical temperature T_c.



(a) (b)

Fig. 3 Loss factor as a function of (a) the moisture content M and (b) temperature T

Skin and power penetration depths

Returning to the simplistic approach of a semi-infinite slab system, as the electromagnetic energy penetrates into the interior of the material it attenuates to an extent depending on the effective loss factor ε_e''. The inverse of the attenuation constant is defined as the skin depth, $\delta = 1/\alpha$, which is the depth at which the magnitude of the electric field drops to 1/*e* of the value at the surface. Fig.2c shows schematically the decay of the electric field and power. As p_v is proportional to $|E_z|^2$, the power dissipated per unit volume decays as the energy traverses the semi-infinite dielectric slab.

$p_v(y) = P_o e^{-2y/\delta} = P_o e^{-y/D_p}$ [9]

where P_O is the incident power density and D_p is the power penetration depth at which the power drops to 1/*e* from its value at the surface At $y=\delta$, eqn.[9] yields $p_v(\delta)=0.14P_o$ giving 86% dissipation (note that $D_p = 1/2\alpha = \delta/2$-see figure 2c). At the frequencies allocated for industrial use in the microwave regime, the penetration depths could be very small indeed and often the size of the dielectric to be treated, particularly when it is fairly lossy, is many times larger than D_p, which may result in temperature non-uniformities. Rough estimates of D_p can be determined by consulting the literature on dielectric properties.

Temperature distribution

Microwave heating entails the conversion of electrical energy to heat either to raise the material temperature to a critical level or for material drying or for material melting, to cite but a few well known examples.

A generalised hear flow equation can be formulated, to describe the temperature or moisture distribution for these processes, containing the following terms: rate of rise of temperature $\rho c\partial T/\partial t$; temperature distribution, $\nabla.\boldsymbol{q}$, through Fourier's law $\boldsymbol{q}=-k_e\nabla T$; volumetric power density generation p_v; as well as an additional convective heat flow term due to any appreciable surrounding gas/solid energy exchange and specific heat and enthalpy of evaporation terms due to the components of a moist dispersed system. Here, ρ and c are the density and specific heat, while k_e refers to the effective thermal conductivity of the material. In the case of unit operations, use is also made of the relevant mass transfer equations of the bound materials[3], where now k_e is a tensor and c is an effective specific heat, both parameters containing contributions of the various components in the heterogeneous mixture.

By taking specific simple cases, solutions can be obtained, say, for the temperature distribution within a heated dry dielectric material after a steady-state condition has been reached or for the moisture levelling in planar dielectrics where, for example, the microwave energy is applied when $\partial T/\partial t = 0$ and where the contributing effect of the Fourier-derived term is ignored.

Numerical modelling

A concerted effort has recently been made to determine the temperature and moisture distribution theoretically during microwave processing[4]. The power density term p, contains the electric field established in the material and strictly speaking the wave equation has to be solved in order to determine the field's distribution[5]. Exact analytical solutions can only be obtained for the most simple cases, in which it is still necessary to assume constant ε_e'', σ_e, k_e, ρ and c parameters[6].

Numerical methods based on finite differences, finite elements, the method of moments or transmission line matrix methods have been used with varying degrees of success. Metallic sheet insert and shields specially used in microwaveable food packages can now routinely be modelled using finite elements[7].

Industrial systems

Typical industrial microwave heating or drying equipment is shown in Fig. 4. Basically there are three major components. The first component is the power unit where microwaves are generated at the required frequency band. The second component forms the applicator, where the material is subjected to intense microwave fields, and to which any additional ancillary process equipment such as pumps for operation under moderate vacuum conditions, steam or hot air injection, must be connected. Often the applicator forms the last part of a conventional processor.

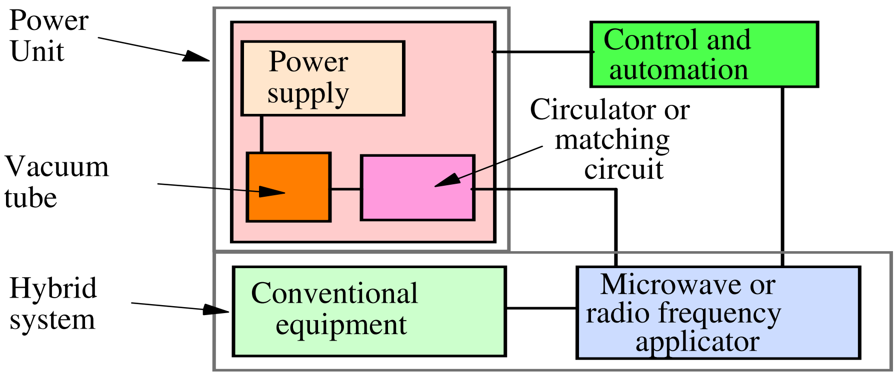


Fig. 4. Typical microwave hearting set-up

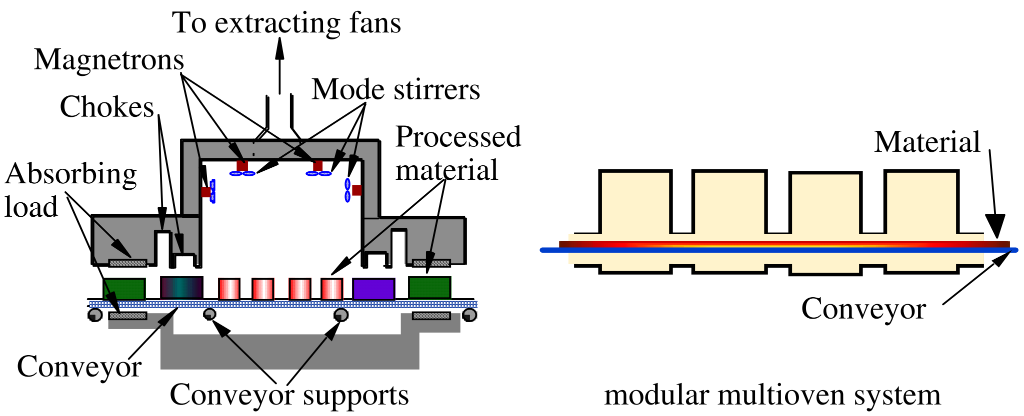
Finally, the third major component is the control circuitry to optimise and regulate the overall performance of the microwave heater. Magnetron tubes are used primarily to generate the microwave power. It is by now usual and prudent practice to incorporate a ferrite iso-circulator protection between the magnetron source and the applicator.

Microwave applicators

The most common form of an applicator, comprising well over 50% of industrial systems, is the multimode type. In principle, it is an extension of the domestic microwave oven but built for large scale material processing. However, industry uses many other types, with a brief description of some of the most popular ones given below[2].

Multimode applicators

Basic application: Multimode resonant applicators consist of a metallic enclosure into which a microwave signal is coupled through a slot and suffers multiple reflections as shown in Fig. 5*a*. The superposition of the incident and reflected waves gives rise to a standing wave pattern or mode. In a given frequency range such an applicator will support a number of resonant modes.



(a) (b)

Fig. 5 Multimode oven applicators (a) basic multimode applicator with four magnetrons (b) modular system

For any empty applicator each of these modes exhibits a sharp resonant response. However, for an applicator partially filled with a dielectric material which couples reasonably to the microwave electromagnetic fields, the resonant responses of the modes will overlap in frequency to give a continuous coupling with the dielectric load. This applicator is very versatile in that it can accept a wide range of material loads of different effective loss factors and sizes.

Coupling systems*:* The energy is coupled into the applicator through a slot, an array of resonant slots, a radiating horn or by other means. To improve the uniformity of heating within the multimode applicator a number of methods are used, such as a mode stirrer. With multiple generators the opportunity exists to distribute the power so as to give a better excitation of the modes and better uniformity of heating than can be achieved with a single feed, by distributing the feed points around the walls of the oven and by feeding at different polarisations. The magnetrons may be mounted directly or through a launching waveguide.

In common with all oscillators the impedance of the load connected to the output affects the performance of the magnetron in both generated power and output frequency. The reactive component of the load impedance causes a small change in the output frequency, whereas the resistive component affects the output power.

These characteristics are displayed in the Rieke diagram, shown typically in Fig. 6, in which contours of frequency and power output ate plotted on an impedance circle diagram. Usually within the permitted load impedance range of the magnetron, frequency and power changes do not exceed ± 0.2% of nominal frequency and ± 15% of nominal output power, respectively.

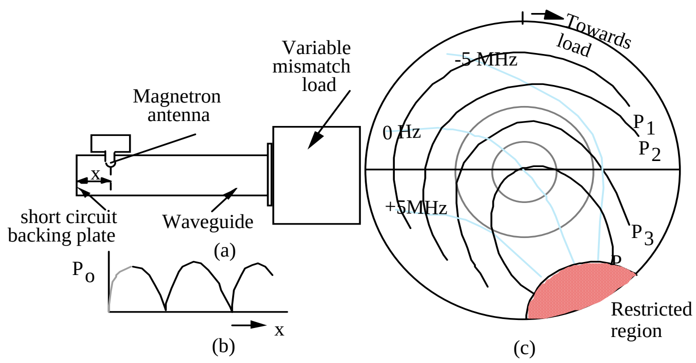


Fig. 6 (a) Waveguide launcher (b) power distribution and (c) Rieke diagram

The position of the back plate of the waveguide is determined by experiment following a set of well documented guidelines whereby the magnetron is substituted by a probe and using a variable mismatch load at the end of the waveguide as shown in Fig. 6a. The power distribution shown in Fig. 6b follows.

In the case where the magnetron is connected to the oven applicator via a waveguide one can fine match the magnetron to the loaded applicator, by substituting the magnetron with a suitable probe and carrying out impedance measurements using a network analyser. Matching adjustments are then made to ensure that operation is kept within the manufacturer's recommended region, shown shaded on the Rieke diagram of Fig. 6c.

The region where the frequency contours converge, called the sink, should be avoided. This is because when the Voltage Standing Wave Ratio (VSWR- a measure of reflections) exceeds the specified maximum in the sink, unstable operation, including moding and frequency jumping, may occur. However, operation in the region of convergent frequency lines outside the sink is desirable to obtain mode shifts in the multimode applicator.

Multimode processing systems*:* A typical online multimode oven applicator for industrial processing of irregular loads is shown in Fig. 5*a*. Leakage of electromagnetic energy is minimised by the use of protective devices such as absorbing loads or reflective devices. In Fig. 5*a* four magnetrons are shown to feed power to the applicator, however, industrial systems with many tens of magnetrons feeding one applicator cavity have been designed.

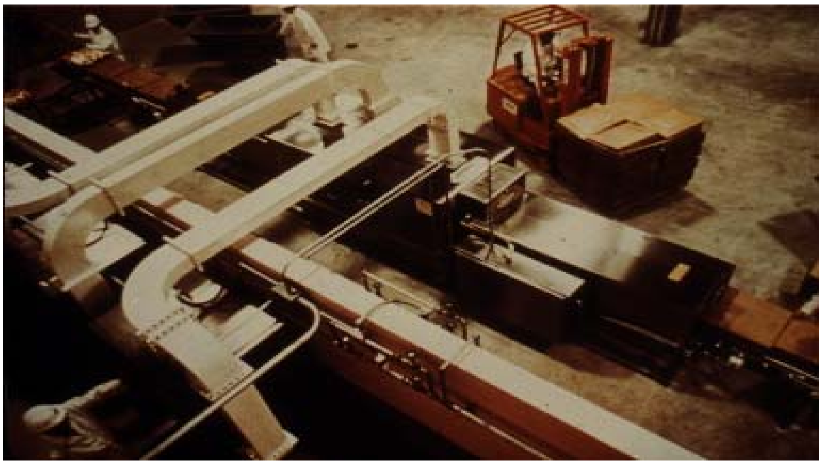


Fig. 7 Continuous microwave meat tempering system
(Courtesy of Selo-Bollans Ltd)

Fig. 7 shows a multi-feed processor for meat tempering at 896 MHz, while Fig. 8 shows a prototype puffing or rapid drying for snack foods. In this latter system a relatively small volume

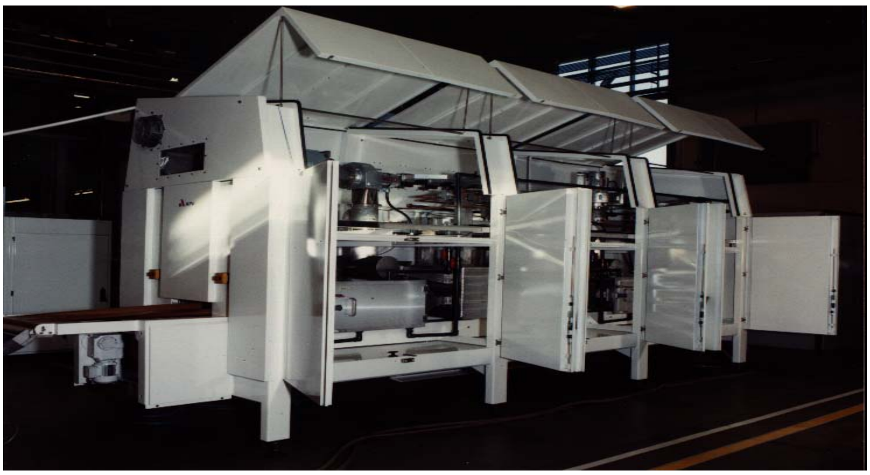


Fig. 8 Microwave puffing system for snack foods

(Courtesy of APV Baker Ltd)

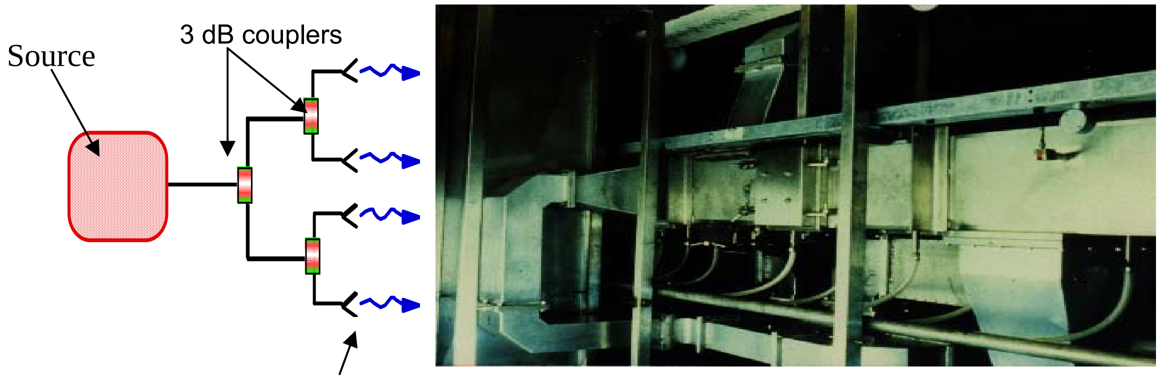
applicator is used capable of being able to handle large amount of power without arcing occurring. Consequently, the high power density produced in the applicator is used for dry-frying of snack foods such as pellets. By bringing the pellets rapidly to 100^{o}C it boils off the moisture and expands them in less than ten seconds. The product is healthier compared to when using oil baths although for organoleptic reasons some oil may be added afterwards for optimising the recipe for microwave processing.

Modular microwave systems have been very popular in that a large microwave processor can be constructed by placing a number of units shown in Fig. *5b* in series and running the material on a conveyor which passes through all the units. Fig. 9 shows such a system comprising two modules for preheating rubber composite extrusions, including metallic spines, prior to vulcanisation in a hot air tunnel. Each module offers the facility of connecting up to 12 kW of microwave power at 2450 MHz in 2 kW steps according to the specific requirement of throughput and type of rubber.

Fig. 9 Modular microwave pre-heater for rubber vulcanisation
(Courtesy of Microwave Heating Ltd)

Horn applicator

Horns can be used effectively to beam the energy into a conveyor tunnel which carries foodstuffs to be processed. In a specific application the energy from the magnetron is split equally four ways as shown in Fig.10a and radiated sequentially from the four sides as shown in Fig. 10*b* towards blocks of foodstuffs, such as meat or butter, for tempering. In such a process the frozen foodstuff is elevated from the cold store temperature to just a few degrees below zero. This avoids defrosting the product, which might lead to thermal runaway on account of the much higher ε_e'' of water compared with that of ice.



(a) (b)

Fig.10 (a) Microwave splitter using 3 dB couplers and (b) continuous microwave butter tempering lines (Courtesy of Anchor Foods Ltd)

In the particular application shown in Fig. 10*b* three separate lines operating at 896 MHz are used to temper 25 kg blocks of butter from -14ºC to about -2ºC, which facilitates further mechanical processing such as blending and portioning 250 g retail packs.

Single-mode resonant applicators

In single (fundamental or higher order) mode resonant cavities the superposition of the incident and reflected waves gives a standing wave pattern which is very well defined in space. This enables the dielectric material to be placed in the position of maximum electric field for optimum transfer of the electromagnetic energy.

A most versatile single mode resonant applicator is shown in Fig. 11, which operates in the TE_{10n} mode. It consists of a rectangular waveguide, into which a co-sinusoidal electric field distribution of *n* half-wavelengths is established, connected to a flange with a coupling iris on one side and a non-contacting short-circuit plunger on the other side.

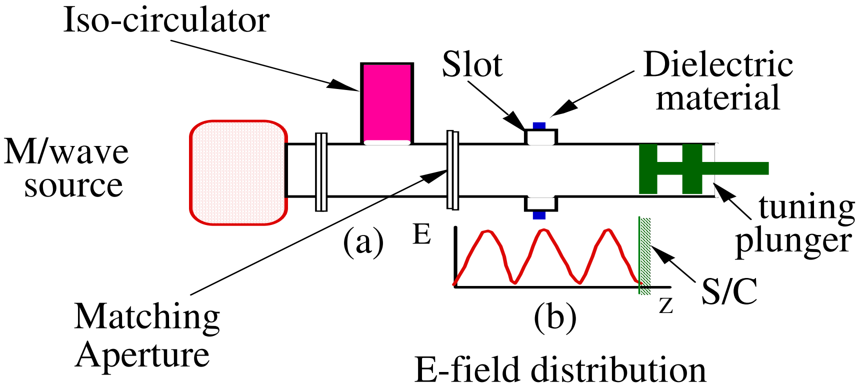


Fig. 11 TE_{10n} single mode resonant applicator

The dielectric material to be processed is inserted into the applicator through a slot in the broad dimension of the waveguide. The dielectric experiences the maximum electric field of the standing wave set up within the applicator, which is in the range $1<E<2$ kV/cm with moderate output power from the source, say a few kW. Larger electric fields, say up to 10 kV/cm, can also be achieved resulting in a very high rate of heating, typically exceeding 30ºC/s.

For optimum performance of such an applicator both the position of the plunger, which determines the operating frequency, and size of the iris, which establishes how much of the energy is in fact transferred to the applicator, are dependent upon the dielectric properties of the material under consideration. Optimisation procedures much be carried out at low power using a network analyser which measures, among other parameters, the reflection coefficient and hence the VSWR and the cavity impedance.

The versatility of such an applicator is unquestioned because a variable plunger and a variable aperture enable this applicator to treat a wide range of dielectrics of different effective loss factors simply by choosing the right dimensions. The system in Fig.11 shows the cavity, with its variable aperture, connected to the power source via an iso-circulator. Infra-red pyrometry measures the surface temperature of a heated sample through a small hole at the side of the waveguide cavity.

Single-mode resonant applicators suffer from the limitation that relatively small size material throughputs can be treated at any one time, even at the 896/915 MHz frequency band, and consequently their adoption in industry has been limited. Furthermore, when processing low loss materials, automatic feedback control systems are necessary to operate within the required resonant frequency band and hence maintain high heating rates. Other less versatile resonant cavities have been used for industrial processing of liquid foodstuffs, for example the TM_{010} or the higher order TM_{020} and TM_{11n} cavities[2].

Special applicators

The use of microwave frequencies has given rise to the possibility of designing applicators to suit every requirement and material configuration. This range from corrugated to periodic applicators and from meander to slow wave or radiator applicators. Moreover, the use of small power magnetrons enables the designer to concentrate the power at specific regions of the processing zone[2].

Review of industrial microwave heating applications

Microwave heating has been established in some key industries. The brief description below highlights the most important applications to date, making reference to Fig.13 where appropriate[1,2]. This review does not include chemical applications where great strides have already been made, particular in organic synthesis[8].

Food tempering

Meat, fish, fruit, butter and other foodstuffs can be tempered for cold store temperature to around -3ºC for ease of further processing such as grinding the meat in the production of burgers or blending and portioning butter packs. The industrial customer cannot eradicate waste from errors in long-term forecasting demand where, for example, too much or too little meat tempered resulted in either wasted meat or lost custom. A typical continuous system is shown in Fig. 7.

Pre-heating for rubber vulcanisation

The temperature of rubber extrusions can rapidly and uniformly be brought up using microwave energy to the required level, for cross-linking of the bonds to commence. The latter process is then carried out using hot air or infra-red energy, as shown by route 1 in Fig.12.

Apart from continuous vulcanisation using modular systems, as shown in Fig. 9, microwaves have been used in batch systems either on a small scale or in multi-magnetron systems to heat blocks of rubber of up to several hundred kg in weight.

Drying

Atmospheric pressure*:* A host of materials from textiles to ceramics and from coated paper to leather have been dried using microwaves, usually in combination with conventional systems as shown by route 2 in Fig. 13. The drying of pasta is an established application comprising three stages involving microwaves and hot air in various combinations, to give improved sanitation and better control as well as quality. Other examples include the drying of onions, parsnips, snack foods (with subsequent expansion as described above in puffing of pellets), fabrics, leather, ceramic cores and moulds and ceramic wares.

Vacuum drying: Some materials are heat sensitive and cannot be dried at atmospheric pressure. It is necessary to reduce the pressure to reduce the boiling point and effect drying at a reduced temperature. A modest vacuum around 100-200 mm Hg is necessary where the formation of a microwave plasma or arc can still be avoided. Notable examples are the drying of fruit juices, beverages, drugs and pharmaceutical pellets.

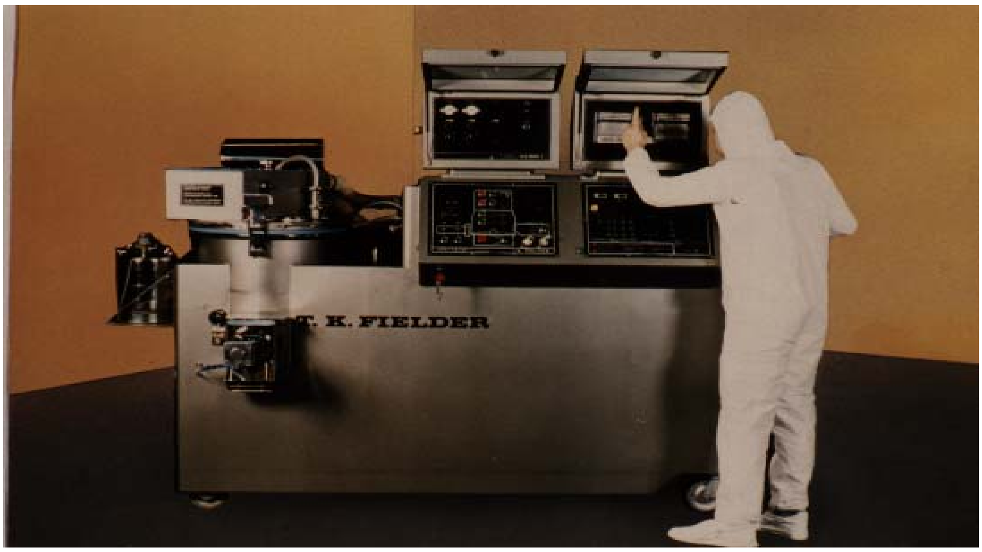


Fig.12 Combined mixing, granulating and vacuum drying system
(Courtesy of Niro T.K. Fielder Ltd)

Fig. 12 shows an integrated processor for mixing, granulating and drying under vacuum a wide range of pharmaceutical products using a 27 kW, 2450 MHz microwave unit. This hybrid processor is highlighted by route 4 in Fig. 13.

Heating and cooking

Many foodstuffs have been cooked by microwaves for various stages of processing. Examples include bacon cooking in a combination system, meat coagulation to upgrade scrap and doughnut cooking for frying.

Pasteurisation and sterilisation

Food products, such as bread, precooked foods and animal feedstuffs have been processed using microwaves for pasteurisation or sterilisation or simply to improve their digestibility. Specific examples include the sterilisation of bonemeal and the processing of barley to achieve starch to gelatine conversion. Food pasteurisation of sealed packs under pressure can be effected by microwave energy, however, as with most pasteurisation processes the product after treatment needs rapid cooling to avoid infestation, as shown by route 3 in Fig. 13.

Potential applications

There are a host of potential microwave applications awaiting better economic conditions to either e revived or be developed further. These include the following areas: food processing, asphalt hole patcher, vitrification of nuclear wastes, treatment of highly toxic substances, waster recover of plastics, pyrolysis, heating of resins, polymerisation, heating of oil sands and the processing of minerals.

Apart from drying other areas of interest in ceramic processing with microwaves include slip casting, sintering of a wide range of ceramics and composites, joining and calcining of superconductors or electroceramics. Microwave energy is presently being used for providing additional heating to the plasma used in thermonuclear fusion reactors and for etching semiconductor products[1].

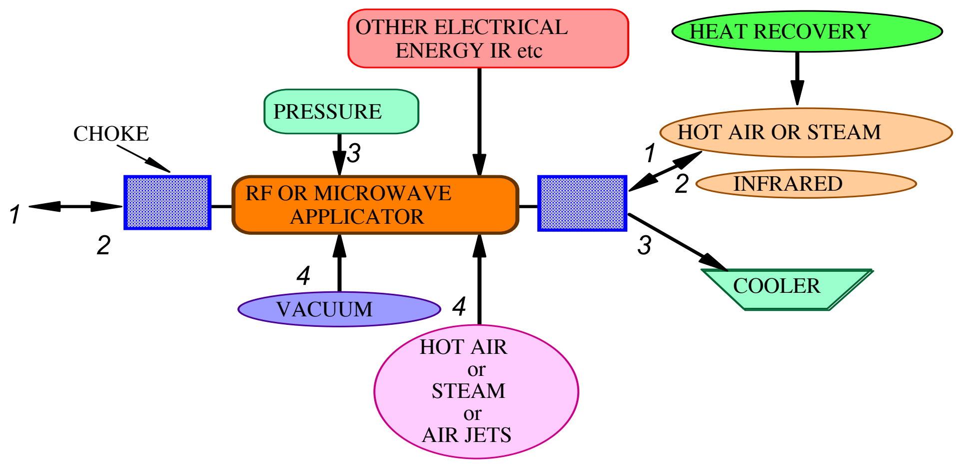


Fig.13 Hybrid systems

Economics

Current industrial equipment capital costs vary between 2000 Euro and 5000 Euro per kW installed, depending on the power range and the level of sophistication of auxiliary equipment required such as backing/diffusion tests sets for the production of a moderate vacuum, injection of hot air or steam, microprocessor control and automation. The overall efficiency, from mains to power dissipated in the product, lies in the range 50-70%. Ultimately, some heat recovery on the conventional hot air unit, as shown in Fig. 13, as well as a careful mix of the various sources of energy available, would enhance the overall system performance.

Conclusions

Microwave heating has been established in a number of industrial sectors. Undoubtedly the food industry with its diverse operations such as tempering, blanching, sterilising, cooking, puffing and vacuum drying offers the biggest opportunity for microwave processing, but the formidable challenge of other competitive techniques must be seriously addressed. Recent developments in the ceramics industries point to major applications which may come on stream involving large microwave power the near future.

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Dr A C (Ricky) Metaxas is a Fellow and Tutor at St John’s College, Cambridge, England, UK. From 1995 until 2005 he was President of AMPERE, the European based organisation which promotes the use of microwave and radio frequency energy in industry and commerce. He is an IEE Fellow.