Dielectric heating for industry

Background

In conventional systems the transfer of heat to a body, whether by convection, radiation or conduction, singly or in combination, can only take place through its surface. Consequently the rate at which the internal bulk of the body heats depends primarily on its thermal conductivity.

Heat transfer often has to be restricted in order to avoid damage due to overheating of the surface. This limit to the temperature gradient between the outside and the inside of a body leads to extended process times, poor equipment utilisation and in some cases batch operations instead of continuous flow.

An alternative approach which can eliminate some or all of the problems is dielectric heating, the generic name covering both radio frequency and microwave sectors of the electromagnetic spectrum (Figure 1). Both are widely used by industry because of their so-called ‘volumetric’ heat transfer characteristics which avoid the need to heat the surface first.

The types of materials and products which can be processed using dielectric heating are basically non-metals which inevitably have poor thermal conductivity. These include food, textiles, paper, ceramics, plastics, pharmaceuticals, chemicals and timber.

The process operations with which it is associated include:

- Welding of pvc
- Curing of wood working adhesives
- Drying of textiles and other bulk materials
- Tempering and defrosting of frozen products
- Curing of polymers & composites
- Pre-vulcanisation heating of rubbers
- Melting of fats and waxes
- Granulation/drying of pharmaceuticals

There are two mechanisms which can contribute to the dielectric loss factor, and so to the heating process (Figure 2). The first is ‘dipolar loss’ which arises from electrical dipoles rotating about their mean position in an applied electric field. The second mechanism is ‘conductive loss’ where electrical charges move from their mean position under the influence of an electric field. The conduction loss mechanism is the same as that in ohmic heating, and is determined by the electrical conductivity of the material. In some circumstances, the conductivity can be controlled; for example by varying the quantity of salt in a product. As can be seen from Figure 3, for water the dipole component is the principal means of energy transfer at microwave frequencies whereas at radio frequencies it is of little significance and the ionic conductivity dominates.

The power transferred to a dielectric is given by:

\[ P = 2 \pi f \varepsilon_0 \varepsilon'' E^2 \]

Where

- \( P \) is the power in watts per m³
- \( f \) is the frequency in Hertz
- \( E \) is the field strength or voltage gradient within the material, in volts per metre
- \( \varepsilon_0 \) is the permittivity of free space = 8.85x10^{-12} F/m
- \( \varepsilon'' \) is the loss factor of the material being heated

Technology

Dielectric heating arises when a high frequency electric field is established within a material which is a poor electrical conductor. The ease with which electrical energy can be transferred to a body as well as the distribution of that energy, depend on the dielectric properties of the various constituent materials which make up the substance. The dielectric properties of interest are the loss factor, \( \varepsilon'' \), which principally determines the amount of energy absorbed by the material for a given electric field. This absorption of heat energy eventually manifests itself as heat.
It is important to realise that the dielectric loss factor is not constant but varies with a number of parameters such as frequency, moisture content and temperature (for example, see Figure 4). It is possible to find information in the literature giving values of loss factors for certain common materials. However, these are normally measured at ambient temperature and at equilibrium moisture content and should be regarded only as a guide, for a material at a given temperature and moisture content, there is usually a frequency (or resonance) which gives a maximum value of loss factor.

For example, water has a maximum dipolar loss factor at about 20GHz. However the loss factor at other frequencies is usually sufficient for an alternative to be satisfactory.

**Available Frequencies**

The frequencies used for dielectric heating are not chosen because of any relationship with the resonance of water or other molecules but are specified by international regulation in order to minimise the risk of interference with telecommunications.

The frequencies available include 13.56, 27.12, 40.68 MHz in the radio frequency band together with 2450 MHz and the ‘900 MHz’ band, currently 896 MHz in the UK, for microwaves. The harmonisation for standards within the EC will mean that 896 MHz will be replaced with a slightly different frequency, possibly 935 MHz with perhaps greater restrictions on emission levels.

**Choice of system**

From observation of the power equation it is apparent that in order to achieve a given power transfer to a material with a particular loss factor there is a trade off between frequency and electric field strength. Since the microwave frequencies are approximately 100 times those of RF, the field strength at microwave will be one tenth of that at RF.
If the loss factor of a material is very low, for example in rubber being heated for vulcanisation or if the process is taking place under vacuum, then microwave must be chosen since the higher voltages at RF make electrical discharge a possibility. However in general terms any system which contains moisture has a loss factor which is high enough for either band to be feasible and other factors such as process design and equipment cost should be used in making the choice. One consideration may be the evenness of heating required, which depends on many things, such as the uniformity of the electric field, the homogeneity of the material and edge effects. Equally important to this uniformity is the penetration depth or the rate of attenuation of the energy within the body.

Whilst this in turn depends on the dielectric properties of the material it is also a function of the frequency of the electric field. In the case of microwave at 2450 MHz operating into a wet body the penetration depth, defined as the distance at which energy falls to 1/e (0.368) of its original value, can be less than 1 cm, whereas at radio frequency it is many times greater. In many applications this is not a matter of concern; in others it must be considered. Whether dielectric heating is suitable for a given product will depend not only on its loss factor but also to great extent on the product dimensions and shape as well as the way in which the electric field can be applied to it. Many judgements have been made on the basis of unsatisfactory applicators and poorly conducted tests.

Radio Frequency Equipment

Radio frequency process heating equipment can be conveniently described as a power supply, or generator, delivering power to an applicator which applies an electric field to the material to be heated.

RF Generators

Traditional standard RF generators consist of a single valve (usually a triode) configured as a self excited ‘class C’ oscillator typically a modified Colpitts, tuned anode/tuned grid circuit.

For valves to operate efficiently, a high positive voltage must be applied to the anode. This is produced from the mains by a step-up transformer and rectifier bridge. Power is drawn from the oscillator through a coupling loop, which is simply a single turn secondary of a transformer of which an inductor in the tuned anode circuit is the primary. This coupling loop is connected to the applicator through a transmission line.

Typical RF generators have a conversion efficiency of about 70% between mains and RF power and single generators producing up to 100kW are available. How much of this is transferred to the product depends on a number of things including the design of the applicator and the degree of optimisation of the coupling. Consequently it is not necessarily easy to use a radio frequency heater, built for a specific application as a general purpose unit.

Valves are either air or water cooled and have a makers guarantee, typical lifetime normally for 2000 hours but in excess of 15000 hours. Modern generators use “50 ohm” technology which utilise solid state systems capable of accurate control.

Applications

The fundamental RF applicator is the “through-field” which consists of a pair of metal plates, normally aluminium or stainless steel, between which the product is placed, as shown in Figure 5. Such a system would be used in a press, for example in plastics welding or wood gluing, in which case there would be no air gap. In other equipment such as a batch or a conveyerised dryer there would be an air gap between the product and the plates. In general the ratio of the space occupied by the material to that occupied by the air should be kept as high as is practicable in order to achieve heating of the product with an electric field strength in the air space which avoids electrical breakdown.

Figure 5. “through-field” applicator

However in some circumstances very small air gaps can also present problems. Several other configurations are available for when the product dimensions or other factors make the use of the through-field system undesirable. These include the fringe field, also known as the stray field array shown in Figure 6 which is used in the processing of thin sheets and webs typically in the paper industry. Another variant is the staggered through-field, also shown in Figure 6 in which the rods are arranged above and below the product, the best known application of this arrangement is in the post baking of biscuits.
These latter two arrays require that the product is transported through in order to achieve uniform heating.

**Microwave Equipment**

Like RF equipment, microwave equipment can be described in terms of generators and applicators. However the technology is very different with the output from the microwave generator being carried to the applicator inside hollow pipes or ‘waveguides’.

**Generators**

The heart of the power supply is the magnetron which converts a rectified high voltage to one of the specified frequencies. Generators at 2450 MHz are available up to 30kW with overall efficiencies of about 70%. The ‘900 MHz’ band generators range from 25 to 100 kW output with claimed efficiencies of up to 80%. Air or water cooling is necessary for all types. The life of a magnetron will depend on many things such as a duty cycle and environment but would typically be between 5000 and 10,000 hours.

**Applicators**

The multimode cavity, often associated with domestic and catering microwave ovens (Figure 7) is widely used in industry.

The microwave energy emanating from the magnetron is launched onto a ‘mode stirrer’ to scatter it to give a more uniform distribution of the electric field at the product. Additional improvement of uniformity may also be achieved by the movement of the product within the oven by, for example, the use of a turn-table or conveyor belt or by multiple microwave positions.

An alternative system which compensates for the attenuation effects in a thick body uses segmented horns aligned in several directions.

When used in conjunction with a conveyor good uniformity can be achieved. Many other designs such as slotted wave guides and single mode cavities can be used for more specialist applications.

**Safety**

RF and microwave engineering is rather specialised and therefore equipment should be constructed by a reputable manufacturer to the relevant standards and recommendations. The design of doors or the inlet and outlet ports are important for both operator safety and prevention of interference.

**Volumetric heating**

Since energy is transferred by the interaction between the high frequency electric field and the responsive components in the substance, heat is generated throughout the volume of the body. True volumetric heating can be seen in many cases although in others, particularly with microwave it is perhaps better referred to as deeply penetrating heat transfer.

**Efficient use of energy**

In a RF system, it is possible to design the system so that power is drawn in the proportion to the amount of responsive material in the applicator, hence there is no energy used when the equipment is empty. When carrying our drying, baking or similar operations the energy output will rise and fall in sympathy with the quantity of water present in the unit, resulting in high efficiencies.

**Improved product quality**

Because it can avoid case hardening and other surface damage because of the volumetric nature of the heating, the quality of a whole range of products, from textiles, ceramics and paper to food and polymers, can be greatly enhanced.

**Equipment suppliers**

Details of suppliers of microwave and radio frequency equipment can be obtained from C-Tech Innovation.

**Benefits**

**Selective heating**

Both radio frequency and microwave will heat water in preference to most substrates with which it is associated. This means not only rapid heating but, in the case of drying, equalisation of moisture content in a product as the wetter areas may absorb more heat that the drier ones.