Electro Heat Techniques Applied to Poor Electrical Conductors: Dielectric Heating

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Abstract: This study illustrates the use and advantages of dielectric heating. The essential advantage of dielectric heating resides in the generation of heat within the material to be heated. In comparison with more conventional heating techniques (hot air, infrared) in which the material is heated via the outer surface, dielectric heating is much more rapid. This is because electrically insulating materials, i.e., the domain of dielectric heating, are mostly also poor conductors of heat. Other interesting characteristics of radio frequency and microwave heating are the high power density and the possibility of selective heating of materials. On the other hand, dielectric heating is a very expensive technique that can usually not compete against other techniques such as resistance or infrared heating concerning costs.

Key words: Dielectric, loss factor, heating, power, conductors, insulating, materials

INTRODUCTION

Radio frequency and microwave heating are electro heat techniques that are applied for heating materials that are poor electrical conductors. Often, they are also poor conductors of heat. In general these materials are known as dielectric materials or dielectrics.

When a dielectric material is brought into a rapidly altering electrical field, heat is generated inside the material. This is known as heating by dielectric hysteresis or, in short, dielectric heating.

Radio frequency and microwave heating are both applications of this principle. In technological terms, however, there is a clear distinction between the two techniques.

The essential advantage of dielectric heating resides in the generation of heat within the material to be heated.

In comparison with more conventional heating techniques (hot air, infrared) in which the material is heated via the outer surface, dielectric heating is much more rapid (Starck *et al.*, 2005). This is because electrically insulating materials are mostly also poor conductors of heat.

POLARISATION

Electrical non-conducting materials (dielectrics) can be dielectrically heated if the molecules possess an asymmetrical structure.

A typical example is a water molecule. In the presence of an electrical field these asymmetrical or polar molecules will orient themselves according to the electrical field.

When a changing electrical field is created, the molecules will try to align with the field and follow the field changing's.

At well-defined frequencies however rubbing will develop between the individual molecules, causing the movement of the molecules lagging the changing electrical field. This leads to internal heat development and an increase of the temperature in the material.

LOSS FACTOR

Not all materials are equally suitable for dielectric heating. The ease with which a dielectric material can be heated is represented by what is known as the loss factor: The higher the loss factor, the more energy can be absorbed in the material.

The name loss factor is derived from electrical engineering and is actually misleading. In electrical engineering, you want capacitors to have a low loss factor (i.e., little internal dissipation).

For dielectric heating, a high loss factor is actually a favourable property. As stated earlier, two phenomena play a role in the dielectric heating of a material:

- The polarisation
- The rubbing between the polarised molecules. Both elements are contained in the definition of the loss factor ϵ.

$$\epsilon = \epsilon'. \tan (\delta) \tag{1}$$

- ϵ' is the relative permittivity or dielectric constant of the material. It is a direct measure of the extent to which the material can be polarised.

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Table 1: Dielectric properties of some materials

Material	Temperature	30 MHz		2500 MHz	
		ϵ'	ϵ''	ϵ'	ϵ''
Water	-12°C	3.8	0.7	3.2	0.003
	+25°C	78	0.4	77	13
	+85°C	58	0.3	56	3
Salt solution	+25°C	76	480	76	20
0.1 Mol					
0.6 Mol	+25°C	75	2400	68	54
Alumina ceramic	+25°C	8.9	0.0013	8.9	0.009
Quartz glass	+25°C	3.78	<0.001	3.78	<0.001
Nylon 66	+25°C	3.2	0.072	3.02	0.041
Polyethylene	+25°C	2.25	<0.0004	2.25	0.0007
Teflon	+25°C			2.05	<0.0005
PVC	+20°C	2.86	0.029	2.85	0.016

- δ is the loss angle and is directly linked to the phase shift between the orientation of the molecules and the changing electrical field as the result of rubbing. For a given material, the loss factor is not a constant value (Riande and Diaz-Calleja, 2004).

It is among other things dependent on temperature, moisture content and frequency. Other properties such as the orientation of the electrical field can also have an effect.

Table 1 gives an overview of the dielectric properties of some common materials.

POWER DISSIPATION

The power that is dissipated in a dielectric material is given by the following formula:

$$P = 2\pi . f . \epsilon_0 . \epsilon' . \tan(\delta) . E^2 \, (W \cdot (m^3)) \qquad (2)$$

f : The frequency of the electrical field (Hz)
ϵ_0 : The dielectric constant of vacuum (8.84•10-12 F m^{-1})
ϵ' : Tan (δ): The loss factor of the material.
E : The rms value of electrical field strength in the material (V m^{-1}).

The above formula only applies strictly to a simple arrangement with two flat plates or for an infinitesimally small volume in the dielectric material. However, in many cases the formula gives a good approximation to the dissipated power, and can be used as an estimate when conducting tests. The formula shows which elements determine the dissipated power: The frequency, the material (i.e., the dielectric properties) and the electrical field strength.

Effect of the loss factor: The dissipated power increases in proportion to the loss factor. In the previous paragraph it has already been mentioned that the loss factor is

dependent on a number of variables such as the frequency of the electrical field, the temperature, the moisture content, etc.

Temperature and degree of humidity are the properties that change most during the heating process and the associated variation in the loss factor can dramatically affect the process.

With increasing temperature, the loss factor will often increase. A material whose loss factor has a positive temperature coefficient (Fig. 1a) will, from a critical temperature Tc, suddenly start to dissipate much more energy, generally at the hottest places. The effect is known as thermal runaway and can damage the product. Critical temperatures often arise around phase changes in the material. The loss factor of food products typically evolves as shown in Fig. 1b.

The sudden transition around 0°C can cause problems with microwave thawing on an industrial scale. As soon as droplets of liquid are formed, energy is preferentially dissipated in those places so thawing proceeds unevenly. To prevent these problems, the heating of frozen foodstuffs is stopped at approximately -4°C. This is known as tempering.

Effect of the field strength: The power dissipation is proportional to the square of the field strength. To obtain a high power density the electrical field must thus be as high as possible. The upper limit is that of the breakdown voltage of air. Dry air (1 atm) breaks down at approximately 3kV mm^{-1} but for safety reasons, radio frequency installations operate mostly with a field strength between 80 and 160 (300) V mm^{-1}. The voltage between electrodes remains in practice limited to less than 15 kv.

The configuration of the electrodes and the homogeneity of the load have a great effect on the local value of the electrical field. In a highly heterogeneous material, the component with the highest loss factor will
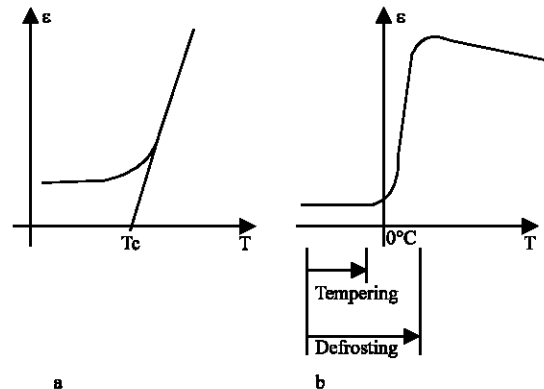

Fig. 1: a) Loss factor with a positive temperature coefficient b) Typical change in the loss factor of foodstuffs

in general absorb the bigger part of the energy. A nice application of this effect is dielectric drying. In a moist material the heat will preferentially be developed in the water. When the moisture content declines, less heat is automatically taken in, so overheating of the material is prevented.

RADIO FREQUENCY INSTALLATIONS

The applicator (or operating space) contains the product that is to be heated. From an electrical point of view, it is a capacitor with a dielectric. Applicators can be constructed in different ways, depending on the specific characteristics of the product or the process. Several configurations are possible, depending on the application (Willert, 2006).

Plate electrodes: The product to be heated is placed between the plates of a flat capacitor. This configuration is mostly used for discontinuous processes such as welding thermoplastics or bonding wood.

Stray field electrodes: In this configuration, the electrodes are produced as tubes or rods. They are located in the same plane as the product to be heated. Successive electrodes have a reversed polarity and the electrical field is horizontal. This configuration enables sufficiently high field strength and thus a high power density to be achieved even in very thin products. Stray field electrodes are mostly used for thin products or thin layers up to 10 mm.
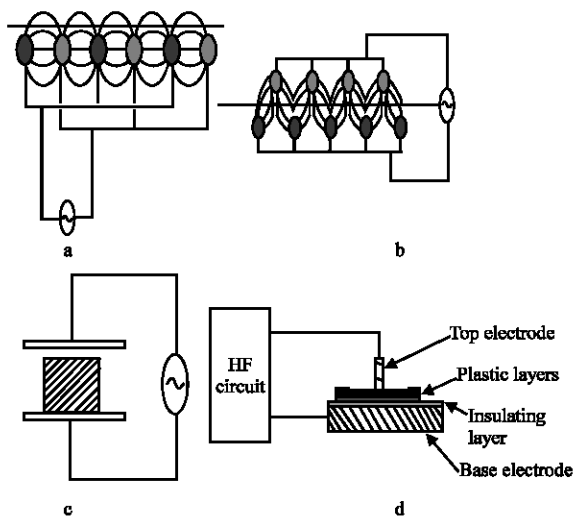
Staggered-through electrodes: The product to be treated is located between two rows of electrodes that are constructed as tubes or rods. The electric field is aligned at an oblique angle to the direction of transport. By doing this higher field strengths can be obtained than with ordinary flat plate capacitors. In comparison with stray field electrodes, this configuration usually offers a more homogeneous field. The field strength can be regulated easily by varying the electrode distance.

Welding electrodes: An important application of radio frequency heating is welding thermoplastics (mainly PVC). The following figure shows a typical electrode configuration (Fig. 2). The items to be seamed are located between a plate-like electrode underneath and a top electrode that is specially designed for the application concerned. Pressure is exerted on the top electrode.

MICROWAVE INSTALLATIONS

Microwave energy-with a wavelength that is comparable with the dimensions of the installation-cannot simply be transported via standard conductors and discrete networks.

Efficient power transmission is achieved with closed wave guides according to the principles of transmission lines.

Wave guides are produced as metal pipes, mostly with a rectangular cross section. The dimensions are dependent on the frequency. Wave guides can be both straight and curved.

To keep the transmission losses to a minimum, metals that are good conductors such as copper or aluminium are used. The inside surface must be smooth and clean.
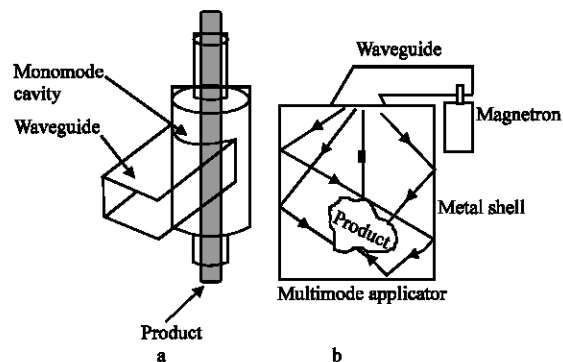
There are two basic designs in microwave installations:

Fig 2: (a) Stray field, (b) Staggered through, (c) Flat plate and (d) Welding electrodes

Fig 3: (a) Monomode applicator, (b) Multimode applicator

- Monomode applicators: the product runs though a folded rectangular wave guide.
- Multimode applicators: a resonating space in which the product to be heated is placed (Fig. 3).

TECHNOLOGICAL DIFFERENCES

Radio frequency and microwave techniques are both based on the principles described above. The operating frequency is however, different. Radio frequency installations operate in the 10-30 MHz frequency range and the associated wavelength amounts to 10-30 m. Microwaves are located in the 900-3,000 MHz range and consequently have a much smaller wavelength: 10-30 cm.

In the radio frequency technique the wavelength is thus greater than the products to be heated and the different components of the installation. The basic concepts from low frequency electrical techniques remain valid for this reason: Currents flow through conductors that are insulated from the earth and electrical fields are generated between electrodes, as in electrostatics (Reusel and Belmans, 2006).

In microwave installations, the dimensions of most components are smaller than, or of the same order as, the wavelength. The basic concepts of low frequency electrical techniques therefore no longer apply and are replaced by the concept of electromagnetic waves: Energy is generated with magnetrons, transmitted via wave guides and emitted from resonating spaces or cavities.

Penetration depth: Generally stated, the penetration depth is smaller for microwave heating because the frequency is many times higher than in radio frequency installations. However the dielectric properties of the material that is to be heated also play a major role.

When electromagnetic radiation strikes an object, part of the radiation will be reflected. The remaining part penetrates into the material and is gradually absorbed (Fig. 4).

The gradual absorption of power is characterised by the penetration depth d. This is defined as the depth in the material at which the transferred power has been reduced to 37% of its original value. To put it another way: 63% of the transferred power is dissipated in a surface layer of thickness d.

The penetration depth is inversely proportional to the frequency, tan (δ) and the root of the relative permittivity:

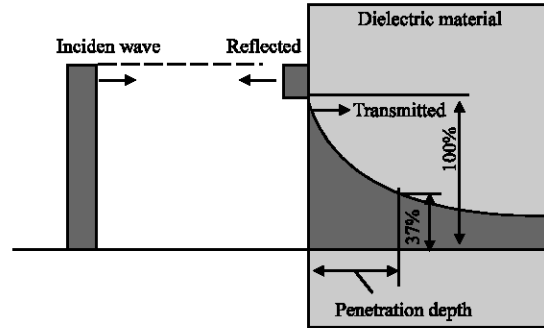$$d = \frac{1}{f.\tan(\delta).\sqrt{\varepsilon'}} \qquad (3)$$

Fig. 4: Power flow when an electromagnetic wave strikes a dielectric material with high loss factor

The final two factors are properties of the material. The penetration depth is smaller if the material lends itself better to dielectric heating.

The depth of penetration can be affected by the frequency, but there are limited opportunities because the frequency bands are sharply defined.

For radio frequency heating (13.56 and 27.12 MHz), the penetration depth is very high, mostly more than 1 m and going up to ten of m. For this reason, radio frequency heating can be seen as being uniform and the idea of depth of penetration is of limited use (Roussy and Pearce, 1995).

It is different for microwave installations that operate at frequencies that are approximately 100×higher. Here the penetration depth is indeed an important parameter and for this reason microwave heating can not simply be regarded as uniform.

Differences in application

Unit power: Radio frequency generators can be constructed with a unit power of up to 900 kW. Microwave generators (915 MHz) are limited to 90 kW. The limit for generators of 2,450 MHz lies around 10 kW. In large microwave installations, several generators are used.

Product geometry: In order to obtain homogeneous heating with radio frequency radiation, the electrode geometry must fully conform to the geometry of the product to be heated. So in practice only products with a regular, simple shape can be considered.

Microwaves on the other hand penetrate the product over their entire surface, except at places in contact with the oven wall or with metal components. Even products with an irregular shape can be heated.

Investments: Both techniques represent a considerable investment cost that is only justified when other heating

techniques do not deliver the desired result. The investment cost for a microwave installation amounts to approximately twice that for a radio frequency set-up.

Efficiency: The efficiency of the two technologies does not differ drastically. In general radio frequency is more efficient than microwaves, but there are exceptions to this rule. In view of the great diversity of applications and the major effect of the product to be heated, it is difficult to give generally valid figures. In the majority of applications the efficiency lies between 50 and 70%.

APPLICATIONS

Plastic welding: Welding of thermoplastics such as PVC or polyamides is by far the largest application of radio frequency heating. Two layers of plastic are placed between a pair of electrodes and welded under pressure.

They can be joined to one another in this way only if the energy absorption by the two plastics is sufficiently high. The power needed amounts to in round figures 1 kW per 25 cm^2 surface to be welded. The electrodes may or may not be cutters and often also serve for cooling after the bond has been made.

Drying veneer: Before veneer can be incorporated into e.g., plywood, the moisture content must be reduced to 7% or less. The standard drying technique with hot air needs a lot of time and does not enable a uniform moisture profile to be obtained. For this reason over drying will often occur. With dielectric techniques a stack of 60 cm can be dried in 10-20 min and a uniform moisture profile can be achieved.

Vulcanisation of rubber: Vulcanisation is a chemical binding process, the goal of which is to give the rubber the desired mechanical properties. The vulcanisation process takes place at a temperature of approximately 200°C and takes rather too long. Good control of the temperature and the process time are crucial

Microwave technology has found wide application in this branch of industry. Because of the volumetric heat effect, microwaves are much more efficient for obtaining a uniform temperature distribution than the conventional vulcanisation techniques with hot air or salt baths (the poor thermal conductivity of rubber makes techniques that use conductive heat transfer difficult).

Mostly a combination of microwaves and hot air is used. The microwaves heat the product up rapidly (e.g., DT of 120 K in 15 sec), after which the product is kept up

to temperature with hot air. The rapid heating ensures higher energy efficiency but also a better control of the product's dimensions.

Microwave installations are used in many different ways in extrusion lines. They enable thick profiles to be heated. They can also be used for profiles with internal metal reinforcing: A special monomode applicator ensures that the electrical field runs perpendicular to the metal.

CONCLUSION

This study has illustrated the use and advantages of dielectric heating. The essential advantage of dielectric heating resides in the generation of heat within the material to be heated. In comparison with more conventional heating techniques (hot air, infrared) in which the material is heated via the outer surface, dielectric heating is much more rapid. This is because electrically insulating materials, i.e., the domain of dielectric heating, are mostly also poor conductors of heat.

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