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HEATING MECHANISM OF MICROWAVE

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ABSRACT
Conduction and dipolar polarization may both give rise to heating under microwave irradiation. Microwave heating is quite distinct from microwave spectroscopy. The photon of a quantum phenomenon excites the rotation levels of gas phase molecules while the absorption of microwave in solid and liquid samples is frequency dependent. The phase difference causes energy to be lost from the dipole in random collision and to give rise to dielectric heating. Heating in metals and metal powders depends heavily upon conduction losses. Magnetic polarization may also contribute to the heating effect.

INTRODUCTION

It has long been known that materials may be heated with the use of high frequency electromagnetic waves (Williams 1967). The heating effect arises from the interaction of the electric field component of the wave with charged particles in the material. Two major effects are responsible for the heating which results from this interaction. If the charged particles are free to travel through the material (electrons in a sample of carbon, for example), a current will be induced which will travel in phase with the field. If, on the other hand, the charged particles are bound within regions of the material, the electric field component will cause them to move until opposing forces balance the electric force. The result is a dipolar polarization in the material. Conduction and dipolar polarization may both give rise to heating under microwave irradiation, and are discussed in more detail below.

It is important to note that microwave heating is quite distinct from microwave spectroscopy. The latter is a quantum phenomenon in which photons of particular energies (and therefore frequencies) excite the rotation levels of gas phase molecules. Whilst the absorption of microwaves in solid and liquid samples is frequency dependent, it is by no means quantized and does not depend upon the direct absorption of microwave photons. Rather, the material behaves as though reacting to a high frequency electric field, and so may be subjected to classical analysis (Daniels 1967, Hill et al. 1969, Hasted 1973, Frohlich 1958, Debye 1929). Details of this analysis are beyond the scope of this introduction, although some of its chemically significant aspects will be introduced and discussed in the following sections.

Dielectric Polarization:

The inability of partially bound charges to follow the rapid changes in a high frequency electric field gives rise to one mechanism of microwave heating. The total polarization **(a_t)** of the material arising from the displacement of charges may be expressed as the sum of a number of components

$$\mathbf{a_t = a_e + a_a + a_d = a_i}$$

Where $\mathbf{a_e}$ results from the displacement of electron charges in relation to the nuclei in a material, and $\mathbf{a_a}$ from the displacement of nuclei relative to one another in materials with unequal charge distributions. Polarization of both $\mathbf{a_e}$ and $\mathbf{a_a}$ operates on timescales which are very much smaller than that required for microwave frequency field reversals, and therefore follow microwave frequency fields almost exactly. As such they do not contribute to the microwave heating effect.

The complex dielectric constant, **ε*,** completely describes the dielectric properties of homogeneous materials and is expressed as the sum of real and complex dielectric constants:

$$\varepsilon^* = \varepsilon' + i\varepsilon''$$

The real part of **ε*, ε',** represents the ability of a material to be polarized by an external electric field. At very high and very low frequencies, and with static fields **ε'** will equal the total dielectric constant of the material. Where electromagnetic energy is converted to heat by the material, **ε''** is non-zero, and quantifies the efficiency with which the electromagnetic energy is converted to heat.

A further quantity, the loss angle **δ,** is also commonly used in the literature, and is more usually given in the form of its tangent. It is related to the complex dielectric constant by; $\tan \delta = \varepsilon''/\varepsilon'$

Where angle **δ** is the phase difference between the electric field and the polarization of the material.

Magnetic polarization may also contribute to the heating effect observed in materials where magnetic properties exist, and similar expressions for the complex permeability of such materials may be formulated.

Dipolar Polarization

Dipolar polarization is the phenomenon responsible for the majority of microwave heating effects observed in solvent systems. In substances such as water, the different electro negativities of individual atoms results in the existence of a permanent electric dipole on the molecule. The dipole is sensitive to external electric fields, and will attempt to align with them by rotation, the energy for this rotation being provided by the field. This realignment is rapid for a free molecule, but in liquids instantaneous alignment is prohibited by the presence of other molecules. A limit is therefore placed on the ability of the dipole to respond to a field, which affects the behaviour of the molecule with different frequencies of electric field.

When the dipole reorientates to align itself with the field, the field is already changing, and a phase difference exists between the orientation of the field and that of the dipole. This phase difference causes energy to be lost from the dipole in random collisions, and to give rise to dielectric heating.

In his theoretical expressions for **ε'** and **ε''** in terms of other material properties, Debye (Debye 1929, Whittaker 1997, Debye 1935) formed the basis for our current understanding of dielectrics.

The dielectric constants, **ε'** and **ε''** are dependent on both frequency and temperature, the first of which is expressed explicitly in the Debye equations whilst temperature is introduced indirectly though other variables;

$$\varepsilon' = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{(1 + \omega^2\tau^2)}$$

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{(1 + \omega^2\tau^2)}$$

Where **ε*** and ε_s are dielectric constants under high frequency and static fields respectively. Since infra-red frequencies are often regarded as infinite for most purposes, **ε*** results from atomic and electronic polarizations, whilst ε_s results from the sum of all the polarization mechanisms described in a later section. The relaxation time, [tau], was derived by Debye from Stoke's theorem;

$$\tau = \frac{4\pi\eta r^3}{\kappa T}$$

Where **r** is the molecular radius, **η** the viscosity, **K** Boltzman's constant, and **T** the temperature.

In solids, the molecular dipoles are no longer free to rotate as they are in liquids, but are restricted to a number of equilibrium positions, separated by potential barriers. Theoretical treatments of this behavior have been formulated and are similar to those developed for liquids. The simplest model for this behavior assumes that there are two potential wells separated by a potential barrier of energy W. This represents the two possible orientations of the dipole. Through statistical mechanics, it is found that the relaxation time is related to the potential barrier by

$$\tau = Ae^{-W/kT}$$

where A is a temperature dependent constant. In fact, most dipolar solids exhibit extremely small dielectric losses since W tends to be extremely large. Water-free ice, for example does not heat significantly under microwave irradiation.

Conduction Effects

In addition to the dielectric losses describe above, many materials may also shown losses through conduction under microwave irradiation. The complex dielectric constant may be expressed to take account of these losses by including a separate conduction term:

$$\varepsilon^* = \varepsilon'_\infty + \frac{\varepsilon'_s - \varepsilon'_\infty}{1 + i\omega\tau} - \frac{i\sigma}{\omega\varepsilon'_s}$$

The importance of this term is displayed by a large number of systems. The addition of dissolved salts in water markedly affects the dielectric properties as conduction increases, and may become important enough to swamp the dielectric losses. On the other hand, the dielectric losses of the majority of solids arise predominantly from these conduction terms, and may be strongly affected by temperature.

The increase in the dielectric properties with temperature is especially important in the microwave heating of solids, as it introduces the phenomenon of thermal runaway. Microwave heating in alumina is poor at room temperature, and dT/dt is therefore small. As the temperature increases so too does the dielectric loss factor and heating becomes more effective (Hamon 1953, Kenkre et al. 1991) and dT/dt increases rapidly. Without careful monitoring of these materials under microwave irradiation, their temperature may rise to undesirably high levels.

Heating in metals and metal powders depends heavily upon conduction losses (Chaudhary et al. 1999) and the important aspects of this phenomenon is treated in greater depth elsewhere.

REFERENCES

Chaudhary A, Khirade P, Singh R, Helambe S N, Narain N K and Mehrotra S C 1999. *Journal of Molecular Liquids,* **82:**245-253

Daniels V 1967. *Dielectric Relaxation,* Academic Press, London

Debye P 1929. *Polar Molecules,* Chemical Catalog, New York

Debye P 1935. *Phys. Zs,* **36**:100

Frohlich H 1958. *Theory of Dielectrics,* Oxford University Press, London

Hamon B V 1953. *Aust. J. Phy,* **6:**304

Hasted J B 1973. Chapman Hall

Hill N E, Vaughan W E, Price A H and Davies M 1969. Van Nostrand Reinhold Co. London

Kenkre V, Skala L, Weiser M and Katz J 1991. *Journal of Materials Science,* **26:**2483-2489

Whittaker G 1997. *Journal Of Microwave Power and Electromagnetic Energy*

Williams N H 1967. *Journal of Microwave Power*, **2**:123