

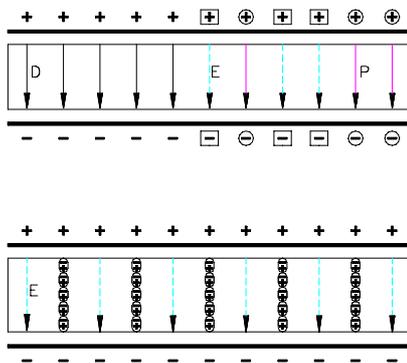
DIELECTRIC HEATING WITH MICROWAVE ENERGY

Contrary to convective heating with steam and hot-air, or even radiation heating in general, dielectric heating generates heat directly inside the exposed material. The conversion of electric energy to heat results from the dielectric losses of the electric non-conducting material, which is usually also a poor thermal conductor. In convective heating of materials with poor thermal conductance properties, the surface has to acquire high temperatures so that the temperature gradient, i.e., the transport of heat, will be as high as possible and account for the material's rapid heating.

The Behaviour of Dielectric Media

Dielectric heating depends on the interaction between polar groups in molecules of non-conductive materials and the alternating electric field of electromagnetic oscillation. The atomic carriers of charges prevailing in fluid and solid materials are not able to move upon imposing an electric field \mathbf{E} , instead, they may only be slightly dislodged from their initial position. The effective force is proportional to the electric field strength, and due to this displacement, negative and positive surface charges arise at the terminal sites. This phenomenon is referred to as polarisation \mathbf{P} and is related to the electric field by the following equation:

$$\mathbf{P} = (\epsilon_r' - 1)\epsilon_0\mathbf{E} = \mathbf{D} - \epsilon_0\mathbf{E} \quad (1a)$$



- $\oplus \ominus$ gebundene Ladungsträger
- $\oplus \ominus$ freie Ladungsträger
- $\oplus \ominus$ Dipol

Figure 1. Dielectric polarisation of a non-conductor in a capacitor

- \mathbf{E} electric field vector
- \mathbf{P} polarisation vector
- \mathbf{D} dielectric displacement vector

Dielectric displacement \mathbf{D} and the electric field \mathbf{E} are in phase. This correspondence is eliminated in an alternating electric field. The real value of the dielectricity constant is turned into a complex value.

$$\epsilon^* = \epsilon_r' - j\epsilon_r'' \quad (1b)$$

hence defining the losses occurring in the dielectric. From this relation we can derive the loss factor $\tan\delta = \epsilon_r''/\epsilon_r'$. ϵ_r' and ϵ_r'' are usually frequency and temperature dependent. ϵ_r'' assumes a more or less distinctly expressed maximal value within a certain frequency range. At the same time, ϵ_r' decreases continually by the value $\Delta\epsilon_r'$ (Fig. 2).

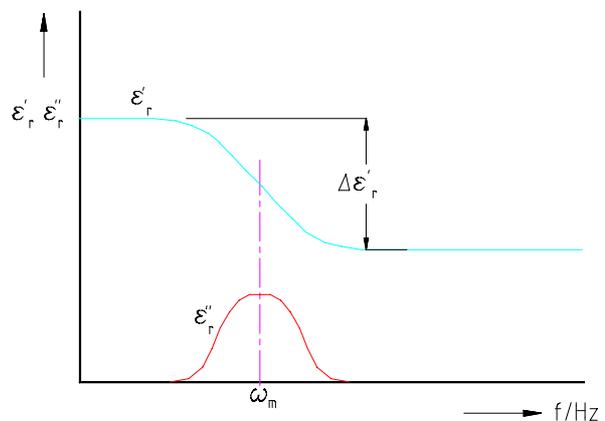


Figure 2: Relative real and imaginary terms of the dielectric constant depending on the angular frequency of electromagnetic oscillations (ϵ_r' -jump of the real term in the environs of natural frequency ω_m)

It depends on the atomic and molecular structure of a given compound in which range of frequency the maximum of ϵ_r'' will lie and how distinct it will be expressed. In this respect, an immediate relation to the polarisation type does exist. In an atom, which nucleus is orbited by negatively charged electrons, and appears to possess neutral charge, the electron is diverted from its original path by an externally applied alternating field, inducing the dipole moment μ of opposite direction (Figure 3a). This type of polarisation is referred to as optical, or electron, polarisation.

The resonance frequencies usually lie in the ultraviolet or visible range of electromagnetic waves.

A different type of polarisation can be observed in molecular groups with two different atoms that combine to a molecule (ion), but which in their entirety do not reveal any external polarisation, because the centres of positive and negative charges have become identical. This is the case, for instance, in the ion-lattice of rock-salt.

Each ion pair constitutes a polar molecule, because the centres of charges do not coincide. On account of the electrostatic lattice charges of the adjacent ion pairs, the

single ion is not to move freely and the dipole is thus kept from rotation. In an externally applied electric field the atoms are displaced from their rigid equilibrium state (**Figure 3b**). Interactions of this kind occur in the infrared range of electromagnetic waves. Additionally, there is a group of molecules that constitute natural polar formations and are, for this reason, referred to as permanent dipole or polar molecules.

The centre of the charges is no longer identical, but separated over the distance l . For a H_2O or a NH_3 -molecule shown in **Figure 3c**, there are two equilibrium states A and B which are kept apart by a potential threshold. The alternating electric field induces a change in their probability of transition. This type of polarisation, called dipole polarisation, occurs in the high-frequency and microwave range of electromagnetic waves. The frequency dependence over the entire spectrum is demonstrated in **Figure 4**.

In order to assess the nature of the electromagnetic phenomenon quantitatively, which is best explained as a wave phenomenon, we need to apply Maxwell's equation to a free dielectric. To this end, consider a domain with the volume V and the surface F in which the dielectric constant ϵ and the permeability μ are functions of space, but not of time, and which is free of electrical charges. The electromagnetic behaviour of the domain is described by Maxwell's equations.

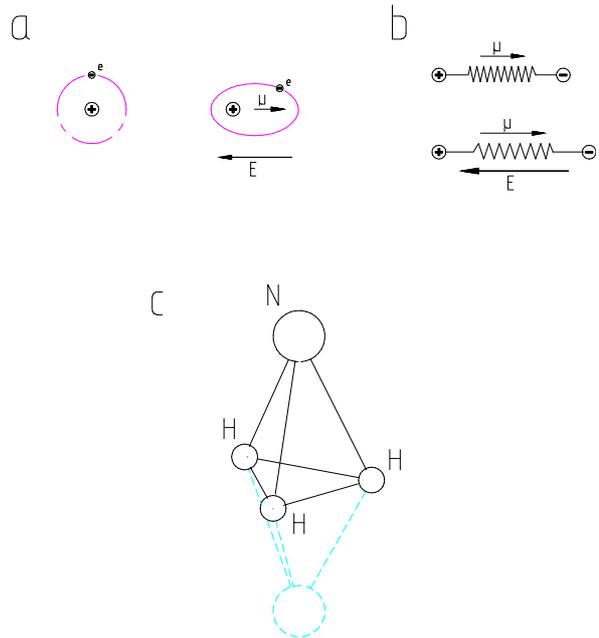


Figure 3a.

Induced dipole moment of an atom
 ϵ charge of the electron
 μ dipole moment

Figure 3b.
Figure 3c.

Induced dipole moment μ of an ion.
Polar NH_3 -molecule with its two equilibrium states A and B

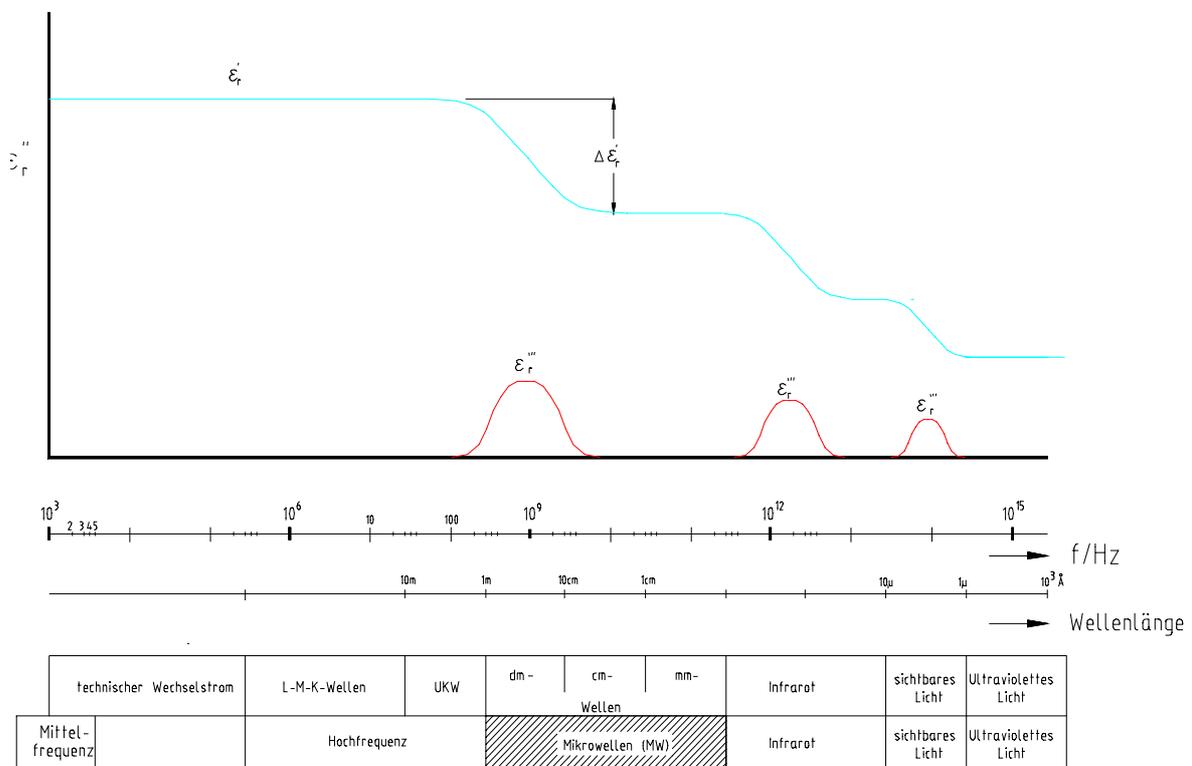


Figure 4. Real and imaginary term of the dielectric constant in relation to the electromagnetic wave frequency

The dielectricity constant ε and permeability μ are depending on their location but not depending from time. The electromagnetic rules of this area are described with the following Maxwell equations.

$$\nabla \mathbf{D} = 0 \quad (2)$$

$$\nabla \mathbf{B} = 0 \quad (3)$$

$$\nabla \times \mathbf{E} = -j\omega\mu_0\mu_r\mathbf{H} \quad (4)$$

$$\nabla \times \mathbf{H} = (\kappa + \omega\varepsilon_0\varepsilon)\mathbf{E} \quad (5)$$

Here, sinusoidal shaped temporary changes are assumed. In a dielectric possessing finite conductivity, the displacement currents can no longer be neglected like in a good conductor, because they are generally much higher than the conductivity currents if the material should be useful as a dielectric. If one wants to learn about the occurring losses, the conductivity currents should not be disregarded. It is therefore necessary to give indication as to the conductivity κ as well as the dielectric constant ε_r' .

$$\nabla \times \mathbf{H} = j\omega\varepsilon_r'\varepsilon_0(1 + \kappa/\omega\varepsilon_r'\varepsilon_0)\mathbf{E} = j\omega\varepsilon^*\mathbf{E} \quad (6)$$

with

$$\varepsilon^* = \varepsilon_0\varepsilon_r'(1 + \kappa/\omega\varepsilon_r'\varepsilon_0) \quad (7)$$

After several vector operations and conversion of the volume integral of $\nabla(\mathbf{E} \times \mathbf{H})$ to an area integral according to the Gaussian equation, we obtain:

$$\int_{\mathbf{F}} \nabla(\mathbf{E} \times \mathbf{H}) d\mathbf{F} = -j\omega \int_V \mu(\mathbf{H}\mathbf{H}^*) dV + j\omega \int_V \varepsilon^*(\mathbf{E}\mathbf{E}^*) dV \quad (8)$$

Activity losses can be calculated by inserting (eq. 6) into the second integral, i.e., the energy converted to heat within a given unit of time. The remnant amount of energy must be applied externally. Hence, the expression standing on the left yields the energy flowing into the volume per unit time.

$$\mathbf{W} = \int_{\mathbf{F}} (\mathbf{E} \times \mathbf{H}) d\mathbf{F} = \int_{\mathbf{F}} \mathbf{S} d\mathbf{F} \quad (9)$$

\mathbf{S} designates the irradiation vector, or Poynting vector, that indicates the direction and the amount of the energy flow in a point of space. The activity losses amount to:

$$\mathbf{P} = \kappa \int_V (\mathbf{E}\mathbf{E}^*) dV. \quad (10)$$

However, due to technical reasons of measurement, and because the properties change with the frequency, it is preferred to express the properties of a dielectric with the two parameters ε_r' and ε_r'' according to equation (1). From eq. (1) and (7) we obtain

$$\kappa = \omega\varepsilon_0\varepsilon_r'' = \omega\varepsilon_0\varepsilon_r' \tan\delta \quad (11)$$

and (10) is turned into

$$\mathbf{P}_{\text{loss}} = \omega\varepsilon_0\varepsilon_r'' \int_V |\mathbf{E}|^2 dV. \quad (12)$$

If an approximately homogenous electric field can be assumed as established within the volume, the well-known relation is obtained

$$\mathbf{P}_{\text{loss}} = \omega\varepsilon_0\varepsilon_r'' \mathbf{E}^2 = 2\pi f \mathbf{E}^2 \varepsilon_0 \varepsilon_r' \tan\delta \quad (13)$$

$$\mathbf{P}_{\text{loss}} = 0,556 \cdot 10^{-12} \varepsilon_r'' \mathbf{E}^2 \times f \quad (14)$$

Equation. (11) and (12) are valid in the whole spectral range of electromagnetic waves. At all times, the dependence of ε_r' and ε_r'' on frequency and temperature must be taken into consideration. Upon penetrating a lossy dielectric the wave will be attenuated and the power dissipated after traversing the distance x by

$$\Delta \mathbf{P} = \mathbf{P}_0(1 - e^{-2\alpha x}), \quad (15)$$

whereby α is referred to as the attenuation constant.

$$\alpha = \omega \sqrt{\frac{\mu'\varepsilon'/2(\sqrt{1 + \kappa/\omega\varepsilon_r'\varepsilon_0} - 1)}} \quad (16)$$

$$= \omega \sqrt{\frac{\mu'\varepsilon'/2(\sqrt{1 + \tan\delta} - 1)}} \quad (16)$$

For smaller values of $\tan\delta$, α will be changed into

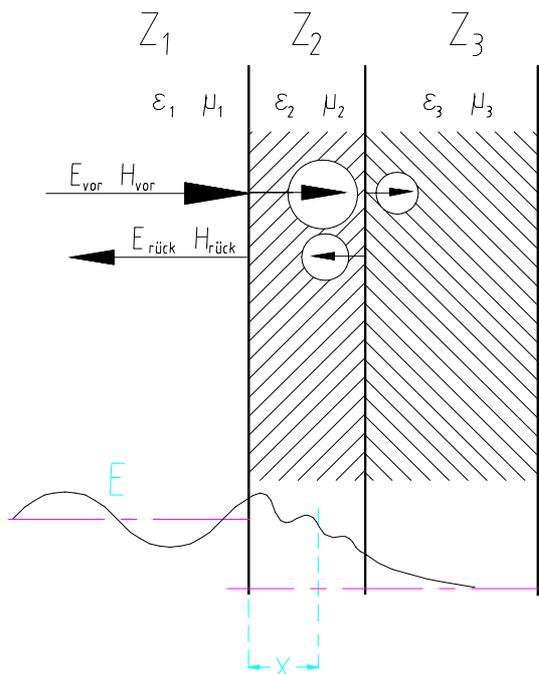
$$\alpha \approx \pi\varepsilon_r''/\lambda_{\varepsilon_r'} \quad (17)$$

The penetration depth θ is the distance after which the power P_0 drops to $1/e$.

$$\theta \approx 1/2\alpha = \lambda_{\varepsilon_r'}/2\pi\varepsilon_r'' = \lambda_0\sqrt{\varepsilon_r'}/2\pi\varepsilon_r'' \quad (18)$$

$$= \lambda_0/2\pi\sqrt{\varepsilon_r'} \tan\delta \quad (18)$$

θ increases proportionally with the frequency f and the dielectric constant ε_r' , as well as with increases of losses. In a mixed dielectric the processes will become very complicated, so that ultimately the experiment will have to decide on the actual prevalent penetration depth. Furthermore, there are influences of the material's conductivity properties which are, for instance, quite obvious in a multi-layered dielectric (Figure 5). One part of the incoming waves will be reflected from the surface if the characteristic impedance of air does not correspond to the respective impedance of the dielectric



The same happens at the joint boundary layer of the two dielectrics I and II if both differ in their characteristic impedance. Reflections will also occur at this interface. The reflected wave interferes in dielectric I with the propagating wave, and forms in this layer a standing wave field with maximal and minimal values, which will cause an uneven temperature distribution. In general, a change of the material's property constants goes along with the temperature rise so that no such (disadvantageous) temperature distribution ensues, instead, maximum and minimum values become blurred (Figure 6). The attenuation of wave energy in proportion to the increasing penetration depth depends on the loss factor ϵ_r'' .

excerpt and slightly modified version of a presentation on the occasion of the V. International Congress on Electric Heating in Wiesbaden, 1993.

pap/re

Bremen 6/97

Figure 5: Propagation of an electromagnetic wave in a multi-layered dielectric. Below: Orientation of the electric field.

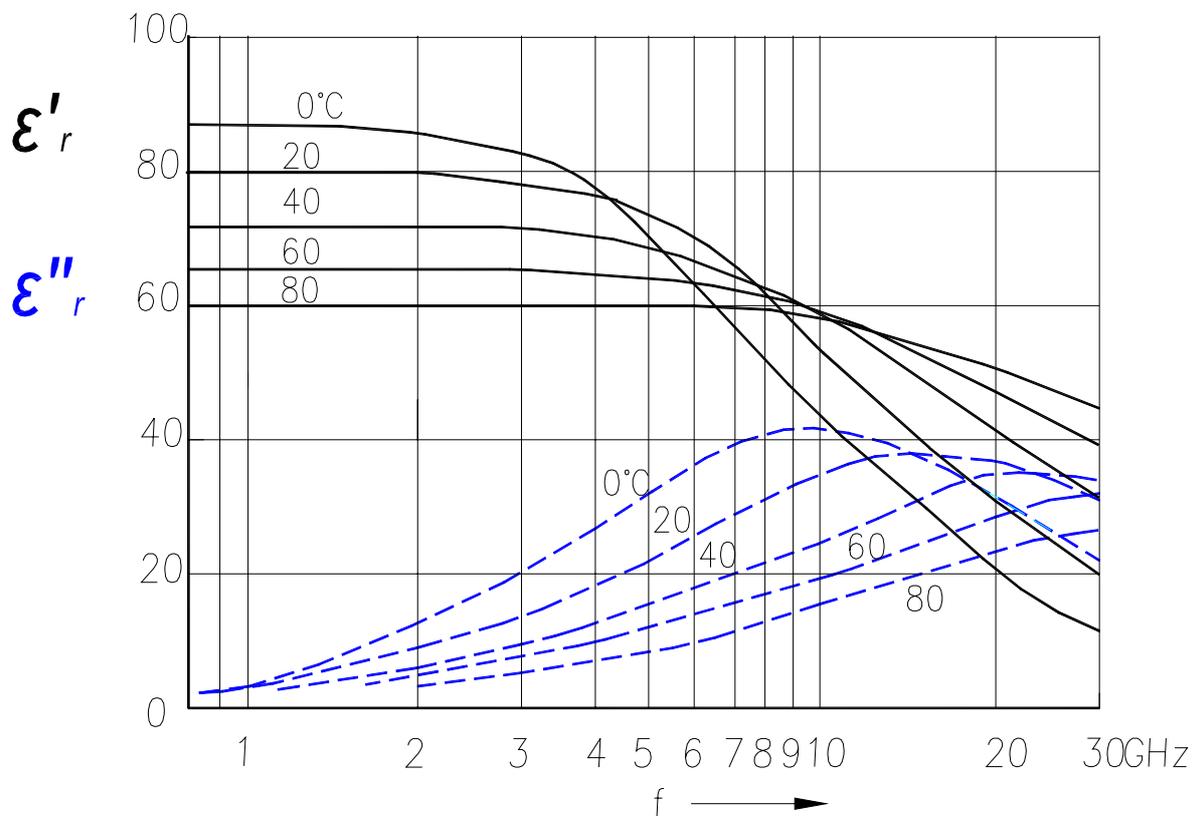


Figure 6: Frequency dependence of ϵ_r' and ϵ_r'' in water influenced by temperature