Study of Electromagnetic Properties of the Agricultural Products

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***Abstract:* During microwave or high frequency heating, many material properties affect the heating performance. Among the most significant are the electromagnetic properties, especially the dielectric properties of the food. In addition to these properties, geometry, packaging, and the microwave oven itself affect the heating. This literature review focuses on multicomponent food products and reheating of prepared foods, but some basic concepts and mechanisms of microwave heating are also introduced.**

***Keywords:* Electromagnetic polarisation, Dielectric properties, agricultural products, Microwave modelling.**

I. INTRODUCTION

The application in the field of information transmission on the electro magnetic support, the transmissions by satellite, mobile phone, using of the electromagnetic radiation in the field of radiofrequencies, the using of the thermal systems with microwaves, are few from the applications which are extending more and more in our days. The most important effect of the electromagnetic radiation, represents the thermal effect, thus this one is of the reasons for which the international bodies has established the norms of security. The researches have noticed some effects on human body, such as: depression, cephalalgie, etc.

Microwaves are part of the electromagnetic spectrum and are located between 300 MHz and 300 GHz. Microwave heating is defined as the heating of a substance by electromagnetic energy operating in that frequency range. The high frequency range, which also can be used for heating, is very large and it can be subdivided into kHz high frequency (10 kHz< f ≤ 1 MHz) and MHz high frequency (1 MHz < f ≤ 300 MHz). The latter range is used here when speaking about high frequency heating. The term radio frequency is used for high frequency mainly in the United Kingdom [10]. The infrared region is located between microwaves and visible light. Only restricted microwave or high frequencies are freely allowed for heating in industrial, scientific, and medical applications, the so-called ISM frequencies [2]. Of these, only 2450 MHz is commonly used in food processing in Europe, while 915 MHz dominates in America and 896 MHz in the UK. Higher frequencies are not in active use, but Decareau [4] has suggested that by combining higher frequencies with lower frequencies it would be possible to get surface browning.

A propagating electromagnetic wave has two components, an electric field (E; unit V/m) and a magnetic field (H; unit A/m). They are vectors and always perpendicular to each other (Fig. 2).

In free space the propagating wave has a velocity (c_0) of about 3.0 x 108 m/s, and this is the maximum speed at which energy can travel. Frequency (f) and wavelength (λ) are linked with the equation:

$$c = \lambda \cdot f \qquad (1)$$

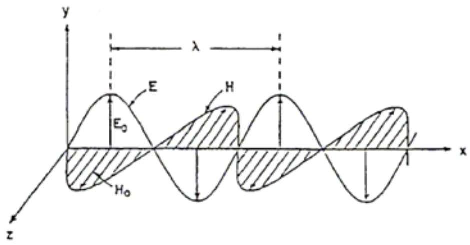

Figure 1. A propagating electromagnetic wave

TABLE 1. Frequency bands of the electromagnetic spectrum.

Field	Frequency	Wavelength
Audio-frequency	$30 - 30\cdot10^3$ Hz	10Mm - 10km
Radio-frequency	$30\cdot10^3 - 3\cdot10^{11}$ Hz	10km - 1mm
Infrared	$3\cdot10^{11} - 4{,}1\cdot10^{14}$ Hz	1mm - 730nm
Visible light	$4{,}1\cdot10^{14} - 7{,}5\cdot10^{14}$ Hz	730nm - 400nm
Ultra violet	$7{,}5\cdot10^{14} - 10^{18}$ Hz	400nm - 0,3nm
X rays	$> 10^{17}$ Hz	< 3nm
Y rays	$> 10^{20}$ Hz	< 3pm
Cosmic rays	$> 10^{20}$ Hz	< 3pm

TABLE 2. The radio-frequency and microwave electromagnetic spectrum delimitation.

Name	Frequency range	Wave length
HF-high frequency	3 MHz-30 MHz	100 m – 10 m
VHF-very high frequency	30 MHz-300 MHz	10 m – 1 m
UHF-ultra high frequency	300 MHz-3 GHz	1 m – 100 mm
SHF-super high frequency	3 GHz-30 GHz	100 mm – 10 mm
EHF-extra high frequency	30 GHz-300GHz	10 mm – 1 mm

II. THE ELECTROMAGNETIC PROPERTIES OF AGRICULTURAL PRODUCTS

A. Polarisation of dielectrics

When two opposite charges are separated by a distance, they constitute an electric dipole. Molecules with non-zero permanent electric dipole moments are called polar molecules. Nonpolar molecules may obtain a dipole moment in an electric field as a result of the distortion of their electronic distributions and nuclear positions. The relative permittivity ε is a measure of the polarising effect from an external field, that is, how easily the medium is polarised. Polarisation (P) can be described by an equation:

$$P = \varepsilon_0 E(\varepsilon - 1) \quad (2)$$

Alberty [1] lists three types of polarisation: electronic, atomic, and orientation polarisation. An important mechanism at microwave frequencies is also ion conductivity (ionic loss or polarisation), where hydrated ions try to move in the direction of the electrical field and transfer energy by this movement. This is strongly temperature dependent [9].

Electronic polarisation comes from the field-induced displacement of the electrons with respect to the nucleus. This polarisation occurs in all substances. In atomic polarisation, the atoms can be moved in crystals or molecules. Electronic polarisation, together with atomic polarisation, gives most dry solids a permittivity of the order of e' < 10. When only these two mechanisms are present, the material is almost lossless at microwave frequencies. Atomic polarisation, which is also called vibration polarisation, is closely related to electronic polarisation but, because of the much greater mass to be moved, the resonant frequencies of atomic polarisation are lower. Atomic polarisation is found in the infrared band while electronic polarisation is found in the optical band. They both are practically independent of the temperature [1], [8].

Many molecules have a permanent dipole moment, and orientation (dipolar) polarisation is due to the partial alignment of these dipoles. Water is a dipole and is usually a major component in biological materials. In a microwave or high frequency field, the dipoles try to follow the rapidly changing field. The dipoles are not completely oriented due to the disorienting effect of thermal motion. This phenomenon is strongly temperature dependent; with rising temperature the thermal agitation becomes more vigorous and fewer dipoles are oriented. The orientation polarisation occurs at microwave frequencies due to inertial forces. [1].

Of all the possible forms of loss mechanisms, orientation polarisation is perhaps the most significant in microwave heating applications at frequencies above 1 GHz. However, this type of polarisation does influence the lower frequency bands as well. Ionic loss typically predominates at frequencies below 1 GHz [8]. With rising temperature, all the phenomena are found at higher frequencies.

B. Dielectric properties

The dielectric properties describe how materials interact with electromagnetic radiation. Natural biological materials absorb only the electric part of the electromagnetic field. Agricultural materials are practically non-magnetic, as they contain only trace amounts of magnetic material, such as iron and cobalt [6], [7].

The absolute permittivity in vacuum is ε_o and it is determined by the speed of light (c_0) and the magnetic constant (μ_0), which are linked by the equation:

$$c_0^2 \mu_0 \varepsilon_0 = 1 \quad (3)$$

The numerical value for ε_0 is 8.854×10^{-12} F/m. In other media (solid, liquid and gaseous), the permittivity has higher values and it is usually expressed relative to the value in vacuum [8]:

$$\varepsilon_{abs} = \varepsilon_r \varepsilon_0 \quad (4)$$

where ε_{abs} is absolute permittivity of a material and ε_r is relative permittivity of a material. It is often recommended that the subscript r, which stands for relative, be eliminated. The high frequency and microwave fields are sinusoidal time-dependent (time-harmonic) and common practice is to use complex notation to express the time dependence [8]. Therefore, the permittivity will also be a complex quantity with real and imaginary components [10]. The equation for complex permittivity is:

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (5)$$

where ε is relative complex permittivity, ε' is relative real permittivity (dielectric constant), ε" is the relative dielectric loss factor, and j is the imaginary component.

The real component of the permittivity, known also as the dielectric constant (ε'), is related to the capacitance of a substance and its ability to store electrical energy. The imaginary component, the dielectric loss factor (ε"), is related to various absorption mechanisms of energy dissipation and is always positive and usually much smaller than ε'. It is approximately proportional to the attenuation of a propagating wave. The substance is lossless if ε" = 0 [7], [8]. The ratio of ε" to ε' is called the (dielectric) loss tangent (tan δ).

The rate of heating can be expressed by the power equation:

$$P_v = 2\pi f \varepsilon_0 \varepsilon'' |E|^2 \quad (6)$$

where P_v is energy developed per unit volume (W/m^3), f is frequency (Hz), and $|E|$ is electric field strength within the product (V/m). The electric field within the product is determined by the dielectric properties, the geometry of the product, and by the oven configuration. Therefore, this equation is generally impractical as the determination of the electric field distribution is very complex [2].

To gain a better practical understanding of the meaning of the values of the dielectric properties, a penetration depth can be calculated from the dielectric properties. Theoretically, the penetration depth d_p (or power penetration depth) is defined as the depth below a large plane surface of a substance at which the power density of a perpendicularly impinging, forward propagating plane electromagnetic wave has decayed by 1/e from the surface value (1/e is about 37 %). If tan δ is smaller than about 0.5, the following simplified formula gives 97% to 100% of the correct value [10]:

$$d_p = \frac{\lambda_0 \sqrt{\varepsilon'}}{2\pi\varepsilon''} \quad (7)$$

where λ_0 is the free space wavelength.

The absorbed power density near the surface of an infinite inhomogeneous slab is, accordingly, approximately proportional to ε'' when ε' does not vary very much. If tan δ is greater than 0.5, the more exact formula should be used [10]:

$$d_p = \frac{\lambda_0}{2\pi\sqrt{2}} \sqrt{\varepsilon' \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'} \right)^2} - 1 \right]} \quad (8)$$

Transmission properties, which are related to the dielectric and thermal properties of the medium, determine the distribution of energy [7]. Since ε' decreases the speed of propagation, the wavelength in the dielectric medium is shorter than in free space. This change in wavelength leads to reflection at the interface between two media with different ε' [8]. The reflection phenomena can be analysed in terms of characteristic wave impedances. Impedance is the ratio between the electric (E) and the magnetic (H) field strengths [9]:

$$\eta = \frac{\eta_0}{\sqrt{\varepsilon}} \quad (9)$$

where η_0 is the wave impedance of free space (approximately 377 W).

The reflection and transmission at a plane boundary are primarily related to square root of permittivity, and the main determining factor for the magnitude of reflection is from the real permittivity (ε') of the material. Errors due to neglecting ε" are less than 5 % for practically all agricultural products [2].

Characteristic impedance is important when different materials are heated simultaneously. The characteristic impedance for the average food is about 50 W. The change in characteristic impedances (the dielectric mismatch) at the food surface results in reflection of about 50% of the microwave power falling on the surface. Most of this energy is reflected back to the seeds via the metal cavity walls.

III. MODELLING AND SIMULATION OF MICROWAVE HEATING

Some installations are synchronized with the network voltage but these are effected by the functional perturbations in the presence of the harmonics of the voltage (some commands at the electrical engines, the invertors command, etc).

Design of food products for microwave heating requires knowledge on fundamentals of microwave heating and many experiments. Mathematical modelling can reduce the timeconsuming experimental part. If models can successfully simulate the heating behaviour of food in a microwave oven, the effects of composition, geometry, and packaging changes can be tested without the cost of sample preparation and testing. Maxwell's equations can be used to calculate the exact electric and magnetic field configuration within the product if the configuration of microwave oven cavity, dielectric properties, and product geometry are exactly known. With the knowledge of physical and thermal properties of the product, and the cooling conditions, the heating pattern could be determined. However, the exact solution of Maxwell's equations could only be obtained in special cases [2]. Generally, a numerical method has to be used.

The alternative solution is to use modelling; the technique breaks down the oven cavity and food geometries into small cells and Maxwell's equations can be approximated and solved for each cell [2]. Earlier the computational capacity has limited modelling, and still today a complete optimisation requires a vast number of simulations. There are many numerical methods but the most common of them are the finite difference time domain (FDTD) method, the finite element time domain (FETD) method, and the moment method (MM). To provide the temperature distribution within the product these models can be combined with thermal simulations. If food has a high permittivity, this may cause stability problems and poor accuracy especially when using the finite element (FEM) or moment methods. Today, the FDTD method seems to be more promising than FEM, especially when comparing the time needed for simulations.

IV. THE FIELD WITHIN THE OVEN CAVITY

More generally, a typical foodstuff in a microwave oven is exposed to the electromagnetic field set up within the oven cavity by the magnetron. These field patterns are very difficult to calculate exactly especially in an oven with a mode-stirring device. Inside such a mode-stirred oven a rotating metal vane scatters the electromagnetic wave resulting in field patterns which are difficult if not impossible to calculate exactly However, the effect of the scattering is to produce electric fields which are, when averaged over time, are spatially fairly uniform. The scattering, although significantly changing the original field patterns, does not attenuate the field and so the power transmitted into the oven cavity remains the same. Consequently, we can make the approximation that exposing the food to the changing field over the course of heating (typically several minutes) is equivalent to exposing the top and sides of the foodstuff to a relatively uniform field imparting the overall same power to the foodstuff as a whole. In contrast in an oven (such as a turntable oven) with no mode-stirring device, and with a waveguide feed, standing wave patterns can arise in the electromagnetic field . Further simulations and experiments into the nature of the field patterns have been conducted in which simulations of a cuboid sample of food exposed to an electromagnetic field fed directly from a waveguide onto the load are reported. These calculations indicate that inside the waveguide an input plane is excited in a TE10 mode and the amplitudes of the incident waves onto the cereals E_y^{inc} are given by

$$E_y^{inc} = E_0 \sin\left(\frac{\pi(x - x_0)}{W}\right) \cos\left(\omega t - \upsilon z_{k_0}\right) \qquad (10)$$

where x_0, y_0 are the coordinates of the corner of the waveguide, W is the length of the waveguide in the x direction, z_{k0} is the location of the excitation plane, ω is the angular frequency of the electromagnetic wave and ν is the wave mode number. The standing wave pattern arising can easily lead to cold spots in the food at nodes in the field. Although the turntable leads to some averaging between the effects of high and low field strengths on the food, it is still possible for the food to be exposed to strongly localised field patterns. An example of these is given by the thermal image presented in Figure 1. Here we see the results of an experiment in which corn seeds has been heated in a 750W turntable oven and heated for five minutes.

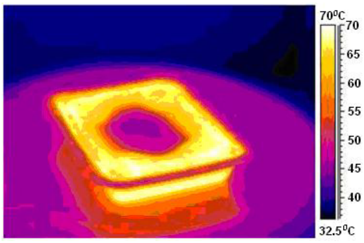

Figure 2: Thermal image of a tray of corn seeds taken after 5 minutes heating in a 750W turntable oven.

In this experiment, the foodstuff was placed at the centre of the turntable. From Figure 1 it appears that there is a minimum in the field at the centre of the oven and the food is rotated around this minimum position, accounting for the region of lower temperature evident in the thermal image. Fully three-dimensional calculations of the field are very expensive and time consuming, and for the purposes of modelling the cooking process it is appropriate to consider some approximations to the field.

V. CONCLUSIONS

There are many publications and databases on the dielectric properties of food materials and model systems. However dielectric data on many food products are still lacking and there are rather few data available on food ingredients [9]. The dielectric data for biological substances have been tabulated [11] for foods and agricultural products [3], [5], [12]. Kent also includes a comprehensive bibliography.

As a complete optimisation of the products would have required thousands of simulations to find the optimal settings of several variables. The results showed that this method has great potential in optimisation of agricultural products and heating appliances.

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