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Relevance of Dielectric Properties in Microwave Assisted Processes

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1. Introduction

Microwaves are electromagnetic radiation with wavelength ranging from 1 mm to 1 m in free space with a frequency from 300 GHz to 300 MHz, respectively. International agreements regulate the use of the different parts of the spectrum; the frequencies 915 MHz and 2.45 GHz are the most common among those dedicated to power applications for industrial, scientific and medical purposes (Metaxas & Meredith, 1983).

Although microwaves have been firstly adopted for communications scope, an increasing attention to microwave heating applications has been gained since World War II (Meredith, 1998; Chan & Reader, 2002). Reasons for this growing interest can be found in the peculiar mechanism for energy transfer: during microwave heating, energy is delivered directly to materials through molecular interactions with electromagnetic field via conversion of electrical field energy into thermal energy. This can allow unique benefits, such as high efficiency of energy conversion and shorter processing times, thus reductions in manufacturing costs thanks to energy saving. Moreover, other effects have been pointed out, such as the possibility to induce new structural properties to irradiated materials (development of new materials) and to apply novel strategies in chemical syntheses (green techniques).

Crucial parameters in microwave heating are the dielectric properties of matter; they express the energy coupling of a material with electromagnetic microwave field and, thus, the heating feasibility (Metaxas & Meredith, 1983; Schubert & Regier 1995; Tang et al., 2002). On the basis of dielectric properties, microwave devices (applicators) can be adopted in heating operations and optimized working protocols can be used.

This chapter is divided into four sections dealing with:

i.   fundamentals of microwave heating and relevance of dielectric properties of materials;

ii.   different techniques used in dielectric properties measurements of materials (test fixtures characteristics, technique applicability, advantages and disadvantages);

iii.   application of the open-ended coaxial-probe method in dielectric properties measurements of food, pharmaceutical ingredients, living materials, to understand specific heating phenomenology and, thus, to optimize thermal treatments / to define safety limits of exposition;

iv.   basics of heat and mass transfer modeling in microwave assisted processes.

2. Microwave heating fundamentals

Peculiarity of microwave heating is the energy transfer. In conventional heating processes, energy is transferred to material by convection, conduction and radiation phenomena promoted by thermal gradients and through the materials external surface. Differently microwave energy is delivered directly to materials through molecular interactions (loss mechanisms) with electromagnetic field via conversion of electromagnetic energy into thermal energy. Whereas loss mechanisms occur, a high rate of heating and a high efficiency of energy conversion are expected. The high heating rate represents the key-feature of microwaves heating, because this makes possible to accomplish in short times (seconds or minutes) what would take minutes, or even hours, to be done with conventional heating. This depends upon slowness of heat delivery rate from the material surface to the core as determined by the differential in temperature from a hot outside to a cool inside. In contrast, use of microwave energy can produce, under some conditions, a bulk heating with the electromagnetic field interacting with the material as a whole. With reference to energy saving, thermal treatments performed by microwave heating can be seen as intensified operations[1].

The ability of a material to interact with electromagnetic energy is related to the material's complex permittivity (dielectric properties or susceptibility). This property, in any homogenous, isotropic, and linear dielectric material is characterized by a frequency-depending absolute complex permittivity usually indicated with the Greek symbol ε:

$$\varepsilon_{abs}(\omega) = \varepsilon_0 \ \varepsilon(\omega) = \varepsilon_0 \left[\varepsilon'(\omega) - i\varepsilon''(\omega) \right] \tag{1}$$

where ε_0 is the vacuum permittivity ($\varepsilon_0 = 8.85 \ 10^{-12}$ F/m) and ω is the angular frequency ($2\pi f$, f frequency, Hz). In scientific literature, complex permittivity is diffusely reported as a relative complex number $\varepsilon = \varepsilon_{abs} / \varepsilon_0 = \varepsilon' - i\varepsilon''$ in which the real part, ε′, is named dielectric constant and the imaginary part, ε″, is known as loss factor. The dielectric constant is a measure of how much energy from an external electric field is stored in the material; the loss

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[1] Process intensification is a current approach in the development of equipment and methods to achieve process miniaturization, reduction in capital cost, improved energy efficiency, and, often, product quality. Additional benefits of process intensification include improved intrinsic safety, simpler scale-up procedures. The philosophy of process intensification has been traditionally characterized by four words: smaller, cheaper, safer, slicker (Coulson & Richardson's, 2002; Stankiewicz, A. & Moulijn J. 2004).

factor accounts for the loss energy dissipative mechanisms in the material[2]. Therefore, a material with a high loss factor is easily heated by microwave. On the other hand, if a material has a very low ε'' is transparent to microwave effect. Power dissipation ($\dot{Q}_g$) is given by the common form of the average power loss density (power dissipation per unit volume, W/m³) drawn from the Poynting's theorem (Metaxas & Meredith, 1983):

$$\dot{Q}_g = \frac{1}{2}\,\omega\varepsilon_0\varepsilon''\,|E|^2 \tag{2}$$

where E is the electrical field strength [V/m]. Bulk heating is achieved when penetration depth (D_p), defined as the distance from the material surface at which the power drops to e^{-1} of its initial value, is of the same order of magnitude of materials dimensions. Assuming electromagnetic field as a plane wave that travels along one axis, penetration depth is calculated as following:

$$D_p = \frac{c}{2\sqrt{2}\pi f \sqrt{\varepsilon'}\left[\sqrt{1+\tan^2\delta}-1\right]^{1/2}} \tag{3}$$

where c is the light velocity in free space (3 10⁸ m/s) and $\tan\delta$ is the loss tangent. Under some conditions (($\varepsilon''/\varepsilon'$) $\ll 1$, i.e. small $\tan\delta$) the penetration depth can be calculated by:

$$D_p = \frac{c}{2\pi f}\frac{\sqrt{\varepsilon'}}{\varepsilon''} \tag{4}$$

When bulk heating is not achievable, a temperature levelling effect can occur in thick layer depending on materials thermal diffusivity that can drive the heat distribution within the whole bulk.

Under a physical point of view, interactions between materials and electromagnetic energy are inherent in the ability of the electric field to polarize the material charges and in the impossibility of this polarization to follow the rapid changes of the oscillating electric field (dielectric dissipative mechanisms). In presence of an external electric field, different kinds of polarization mechanisms are possible: the electronic polarization, caused by modification of electrons position around the nucleus; the atomic polarization, related to positional shifts of nucleus due to the non-uniform distribution of charges within the molecule; the orientation polarization (dipoles rotation) due to the reorientation of the permanent dipoles under the influence of the electric field; the spatial charge polarization observed in materials containing free electrons confined on surface (Maxwell-Wagner effect) (Metaxas and Meredith, 1983). Depending on frequency, one or two mechanisms dominate over the others. In particular, among the dielectric mechanisms of energy dissipation above outlined,

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[2] The loss tangent ($\tan\delta = \varepsilon''/\varepsilon'$) is frequently used in dielectric heating literature providing indications of how the material can be penetrated by an electric field and how it dissipates the energy in heat.

the dipoles rotation is the dominant polarization mechanism in irradiating materials rich in water (such as biological tissues, foods, mixtures based on water or polar solvents) in the microwave electromagnetic spectrum region (industrial high frequency heating $10^7 < f[Hz] < 10^9$). In the same region also ionic dissipative phenomena (Joule's loss effect) may occur if ionic species are present, and can be lossy. The atomic and the electronic polarization mechanisms are relatively weak, and usually constant over the microwave region (Fig. 1.).

Being in dielectric measurements difficult to separate conduction losses from those due polarization, the overall dissipative feature (loss factor) of a material can be expressed by the following equation:

$$\varepsilon''_{measured}(\omega) = \varepsilon''_{ep}(\omega) + \varepsilon''_{ap}(\omega) + \varepsilon''_{dp}(\omega) + \varepsilon''_{int\,erfp}(\omega) + \frac{\sigma}{\varepsilon_0 \cdot \omega} = \varepsilon''(\omega) + \frac{\sigma}{\varepsilon_0 \cdot \omega} \quad (5)$$

where the subscript *ep*, *ap*, *dp* and *intefp* refer to electronic, atomization dipolar and interfacial polarization mechanisms, respectively; and σ is the conductivity of the medium.
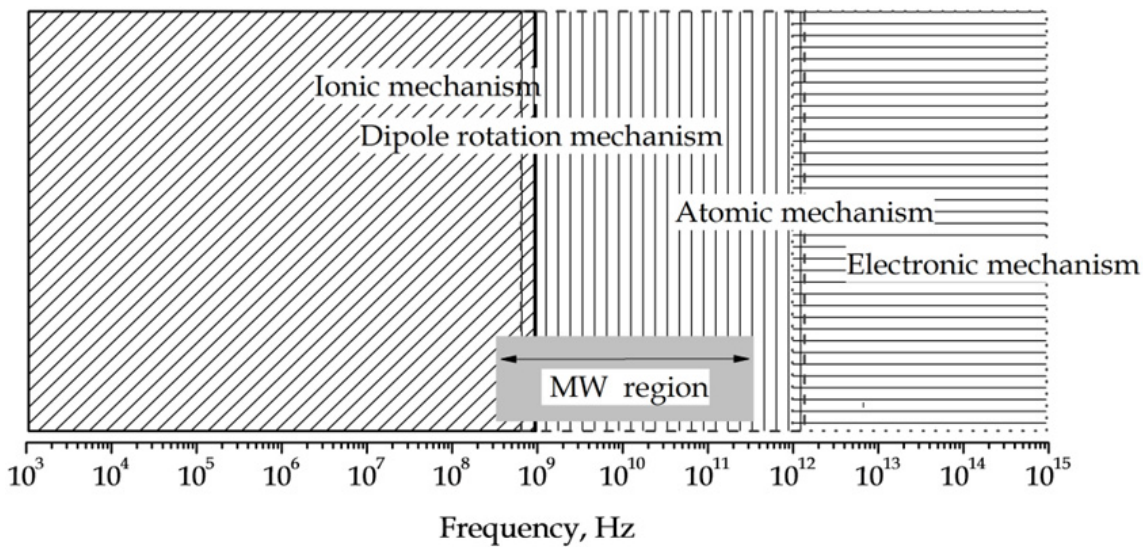

Figure 1. Typical frequency-regions of the loss mechanisms.

Microwave heating processes are currently applied in many fields: from food industry, including packaging (Tang et al., 2002; Schubert & Regier, 2005) to materials processing (polymers, wood, ceramics and composites) (Zhou et al., 2003); from minerals treatments (Al-Harahsheh & Kingman, 2004) and environmental remediation processes (soil remediation, toxic waste inertization) (Kulkarni et al., 2008; Remya & Lin, 2011; Barba et al., 2012) to pharmaceutical emerging technologies (McMinn et al., 2005; Auriemma et al., 2011). Key of all processes above is the energy transfer that, as first discussed, is based on the ability of a material to store and to dissipate electromagnetic energy. Knowledge of the dielectric properties appears fundamental for heating treatments because they have a crucial role in designing (or choosing) of microwave devices (applicators) and on setting operative

parameters (time of exposure, power). Moreover, as dielectric properties can be affected by many factors including frequency of microwaves, temperature, chemical composition of the materials (abundance of water, salt content and other constituents) (Kraszewski, 1996; Chan & Reader, 2002; Tang et al., 2002), microwave heating requires to be appropriately addressed on the basis of dielectric behaviour studies.

3. Dielectric properties measurements

Studies on materials dielectric behaviour are performed by measurements using dedicated instruments and methods. In particular, several techniques have been developed to measure the dielectric properties of materials in the microwave region. They are fundamentally based on the use of vector network analysers (VNA). These instruments, today managed via personal computer, are able to perform measurements of reflection/transmission by opportune test-fixtures. Starting from acquired signals and implemented electromagnetic model, dielectric properties are calculated via software. It is possible to operate with different kinds of test-fixtures developed for various classes of material such as fluids, powders, films. Then, the same general consideration in choosing technique/fixture must be adopted (i.e. destructive *vs* non-destructive analysis; isotropic *vs* non-isotropic samples, permeability or permittivity as relevant property)[3].

In the following sub-sections different measuring methods are briefly presented emphasizing applicability, advantages and disadvantages. In all methods calibration procedures must be performed to reduce systematic errors.

3.1. Open-end coaxial line method

A VNA is connected via coaxial cable to an open-end coaxial probe. To perform measurements the technique requires to press the coaxial probe against the sample material (Fig. 2). The microwave signal launched by the VNA is reflected by the sample and basing on the reflected waves, both dielectric constant and loss factor are calculated. The main advantages of this technique are that it is easy to use, is non-destructive, is very fast and has a reasonable accuracy (± 5%). It is well suited for samples with flat surface (best for liquid or semisolids) with homogeneous features and with not so high dielectric constant or too low loss factor. It requires little or no sample preparation. Since the coaxial probe is produced with rugged structure and materials, the technique also allows to perform measurements in a wide –40 to +200° C temperature range and for corrosive or abrasive materials. On the other side, by the open-end coaxial probe technique, samples with rough surfaces, very thin or anisotropic structures, or at high temperature or with permeability features cannot be investigated. Moreover, use of an open-ended coaxial probe device requires strict operative conditions: cable stability (no flexing of the coaxial cable must occur); absence of air gap between probe and samples surface (absence of bubbles in liquid samples and flat surface in

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[3] Technical brochures of VNA manufacturers are useful in fixtures choices, uses, instruments better performances. As an example see: *http://cp.literature.agilent.com/litweb /pdf/5989-2589EN.pdf* (Agilent Technologies company).

solids and semi-solid samples); use of appropriate sample thickness (measurements must be performed on a "semi-infinite" sample).

Globally, this technique is most commonly used by the research community, especially in microwave food processing, for the features above presented and for the affordable cost of the open-end coaxial probe fixture.

3.2. Transmission line method

Transmission line method requires a VNA connected with a coaxial or rectangular wave guide where the sample under investigation completely fills the wave guide cross section. Dielectric measurements are based on the change of impedance and propagation characteristics of microwave signal launched by the VNA. This method can give accurate measurements and provides both permittivity and permeability measurements, but requires a careful sample preparation (no air gap at fixture walls is tolerated). The method is more expensive then the open-end coaxial probe system (referred to the same range of frequencies), is not easy to use and is time-consuming. Finally, samples with low loss cannot be investigated.

3.3. Free space method

When the contact between fixtures and sample under investigation is not possible (corrosive materials, high temperature) dielectric and also permeability measurements can be performed using the free space method. This method is applied using a VNA connected to two antennas that "see" the interposed samples. The free space method, thus, has the potentiality to perform on-line dielectric behaviour studies of materials under treatments, as an example, in furnaces. The method is not destructive but requires homogeneous, large and flat samples (films, slabs).

3.4. Resonance cavity method

VNA is connected with a resonant cavity where the sample under investigation is placed. This method is based on the shift of the center resonant frequency and the alteration of the cavity quality factor due to the presence of the material in the cavity. It is suitable to investigate very small samples and low loss materials (it also provides permeability measurements) that cannot be investigated with the methods above reported, globally, giving an accuracy of ± 2-3%. This method has complex procedure, requires shaped samples (destructive analysis) and the fixture is more expansive than the open-end coaxial probe.

4. Applications of the open-ended coaxial-probe method

In the following sub-sections examples of dielectric proprieties measurements are presented and discussed. In particular, dielectric spectroscopies of different materials (fruits and vegetables, pharmaceutical mixtures, biological tissues) are performed with the aim of investigating their behaviour when exposed, at given conditions, to microwave irradiation.

Measurements are carried out to respond to two different purposes: to develop *ad-hoc* working protocols (in unit operations based on microwave heating such as blanching, cooking, drying) and to evaluate electromagnetic risks for living tissues if exposed to electromagnetic phenomena (specific absorption rate, SAR, estimations).

Being the materials under investigation basically aqueous, notes on water and saline solutions dielectric behaviour are reported in the first sub-section. In particular, the role of frequency temperature and salt content is emphasized.
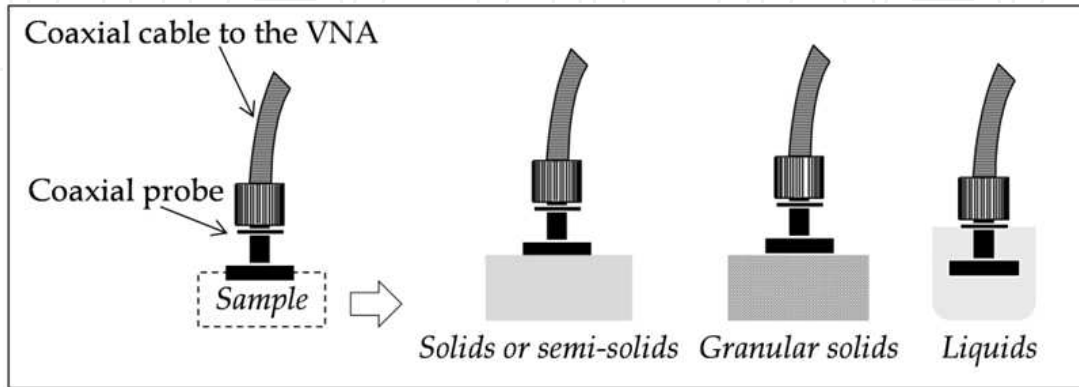

Figure 2. Sketch of coaxial probe position *vs* material under test during dielectric properties measurements.

Note that all the investigated materials are subjected to dielectric spectroscopy in the frequency range 200 MHz – 6 GHz using an open-ended coaxial probe device (Agilent Technologies mod. 85070D) connected to a VNA (Agilent Technologies, mod. ES 8753). Due to the similar nature of the investigated materials, the instrument calibration procedure was performed using the same standards: air; distilled water at 25°C and short circuit block. In Fig. 2. a sketch of the open-end coaxial probe coupled with different samples under investigation is reported.

Even if calibration protocol ensures the removal of systematic errors, additional sources of errors can affect the accuracy of this measurement method. In particular, as reported above, the use of open-ended coaxial probe device requires the operative conditions of: cable stability, absence of air gap between probe and samples surfaces, appropriate sample thickness. A rough estimation of this latter parameter can be calculated by:

$$\text{Sample thickness} = \frac{1}{0.05 \cdot \sqrt{|\varepsilon|}} \text{ [cm]} \tag{6}$$

where $|\varepsilon|$ is the module of the expected complex permittivity. Higher loss features will require lower sample thicknesses.

4.1. Dielectric properties of water and saline solutions

Water is a medium constituted by natural dipoles which can become polarized under application of electric fields orienting the molecules. Dielectric spectroscopy of distilled

water at different temperature is reported in Fig. 3. (Mudgett, 1986; Barba & d'Amore 2008). Al low frequencies ("static" region), water dipoles have enough time to follow variations of the applied field and dielectric constants are at their maximum value (maximum energy of the external source is stored in the material) whereas loss factors are characterized by very low values, approaching zero. Similarly, at high frequency ("optical" region, towards the region of infrared and visible radiations) water dipoles fail to follow the rapid oscillations of the external applied fields so a reduction in polarization effect occurs. This is manifested by the low values of the dielectric constants and of the loss factors low values, i.e. about 5 and zero, respectively. In the intermediate region, known as dispersion" or "relaxation", the dielectric constants decrease as the frequency increases, passing from the static value to the optical one. In this region the dipoles pass from one situation in which are apparently undisturbed because they fully restore their original position during field reversals, to a situation in which they are really undisturbed because the stresses are continuing at frequencies too high to allow the orientation and then relaxation. In intermediate conditions, instead, microwaves frequencies are able to induce phenomena of orientation and consequently of relaxation. In particular, in this spectral region, water loss factor shows a maximum, localized in correspondence of a critical frequency, f_c, which corresponds to a critical wavelength, λ_c. For water at 25°C, the critical frequency is about 18 GHz and the critical wavelength corresponds to 0.017 m. Orientation and relaxation phenomena are thus strongly a function of microwaves frequency. A key parameter used to define orientation effect is the relaxation time τ. It represents the time required to relax the dipolar orientation produced by a static electric field, starting from the removal of the field up to a percentage equal to $1 / e = 0{,}37$ of the initial value. The relaxation time is related to the frequency critical wavelength by:

$$\tau = \frac{1}{\omega_c} = \frac{1}{2\pi \cdot f_c} = \frac{\lambda_c}{2\pi \cdot c} \tag{7}$$

where ω_c is the angular critical frequency ($\omega_c = 2\pi f_c$) and c is light velocity in free space ($c = 3 \cdot 10^8$ m s^{-1}). Relaxation time is a decreasing function of temperature (the critical frequency shows a shift towards high frequencies as temperature increases). Temperature affects both water viscosity and bulk Brownian motions whose variations increase the mobility of the water molecules. By this way water dipoles can easily escape to the orienting action of the applied fields, thus leading to a decrease of the dissipative effect (see also reduction of dielectric properties values). Relaxation time dependence from temperature can be evaluated according to a law Arrhenius type equation (Tang et al., 2002):

$$\tau(T) = \frac{A}{T} \exp\left(\frac{B}{T}\right) \tag{8}$$

where A and B are parameters and T is the absolute temperature [K].

An advantage of the decrease of the dissipative character at high temperature is the achievement of the so called "leveling effect" which, depending from thermal properties of materials, can drive a heat redistribution. This phenomena may play an important role in

the heating processes: if dielectric losses cause a local overheating (hot-spot), a corresponding decrease of dissipative features occurs and, in turn, the growing importance of conductive and convective transport mechanisms contribute to a better heat distribution.
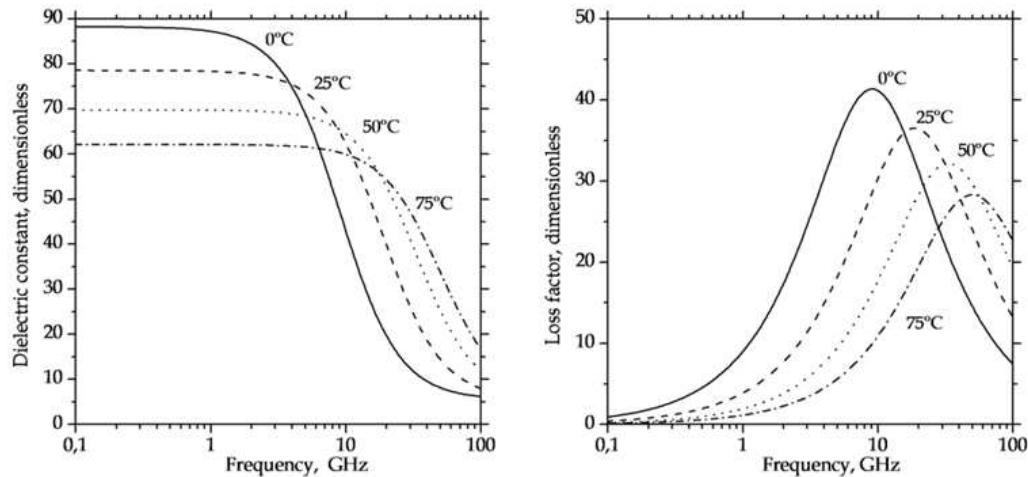

Figure 3. Dielectric spectroscopy of water (dielectric constant on left, loss factor on right) at different temperatures (Barba & d'Amore, 2008, redraw from Mudgett, 1986).

It is important to note that even if dielectric relaxation of liquid water has been extensively studied, the dielectric properties of water in bulk are not of any major significance in industrial microwave heating applications since the relaxation of bounded water is far more important for the majority of applications (Metaxas & Meredith, 1983). Nevertheless, knowledge of parameters that affect dielectric dissipation phenomena (see also dielectric properties) are basilar to understand the relative predominance of the different loss mechanisms at allocated frequencies for industrial, scientific and medical purposes.

Indeed, in many cases it is of interest to treat materials in which liquid water may be present at free and bounded state. Because of the greater difficulty with which the dipoles oscillate due to interactions with the molecules of materials, bounded water presents longer relaxation times (critical frequency is shifted towards lower frequencies thus maximum values of loss factors are achieved under 18 GHz). Fig. 4. depicts, qualitatively, the classical relationship between loss factor and moisture content of a material. Distinct inflexion points in the profile demarcate the transition between the changing states of water in the material. Generally, at low moisture content water primarily exists in bounded form, thus possessing a limited mobility in the presence of electromagnetic waves. As moisture content in material increases, a critical level (or critical moisture content, M_c) is attained. Physically, this means that all the available binding sites for water molecules becomes saturated. Further additions of water beyond this critical level result in an increase in population of free water molecules and consequently in an increase of dielectric losses. In many cases, dielectric properties measurements are performed to determine the M_c of solid mixtures.

The effect of temperature on the bounded water shows an opposite trend with respect to the one exhibited from free water. In fact, the dielectric properties increase with temperature, since the bounded dipoles become free from links and more available to the orientation

effects induced by applied electromagnetic fields. This physical behavior is called "thermal runaway" and, briefly, can be described as a progressive increase of loss features of heated material. Thermal runaway, if not properly taken into account or controlled, can have deleterious effects because it promotes overheating phenomena.
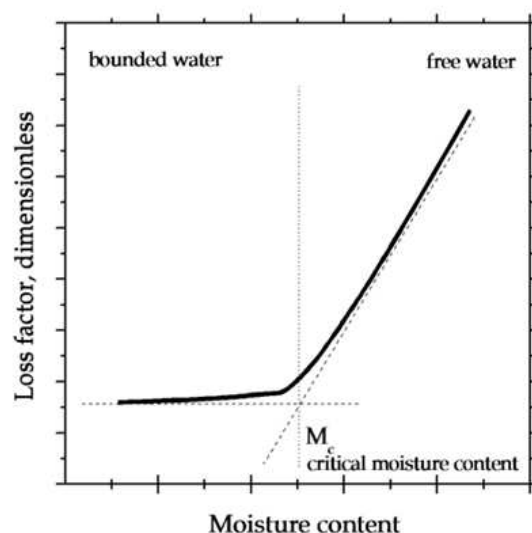

Figure 4. Qualitative relationship between moisture content and loss factor. M_c refers to the critical material moisture content.
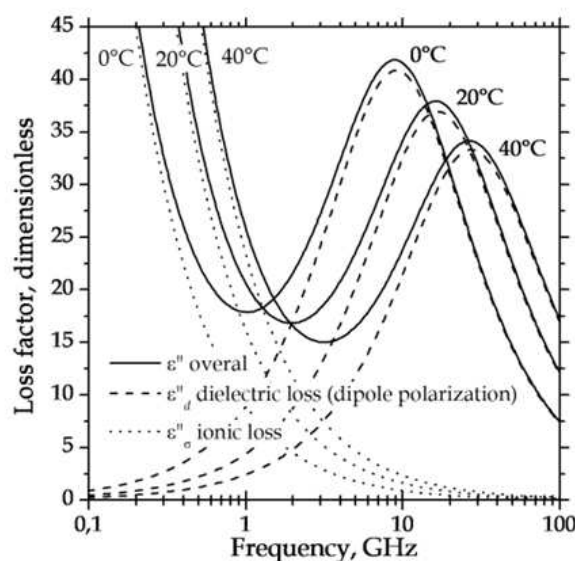

Figure 5. Ionic conduction and dipole polarization loss mechanisms as a function of temperature in NaCl water solution (Barba & d'Amore, 2008, redraw from Mudgett, 1986).

Presence of ionic species is another relevant aspect to consider if aqueous materials are exposed to microwave fields. Presence of ions in liquid or in wet solid bulks, in general, involves decreases of dielectric constant values and increases of loss features. Decrements of the energy-storage ability are due to subtractions of water dipoles, because solvation effects occur (less dipoles can be polarized); loss factor values increments are due to the enhance of

ionic dissipative mechanism, especially at low frequencies. Both described effects increase with increasing temperature. Effects of ionic species in water bulk, at different temperatures, are investigated by NaCl solutions dielectric measurements (Mudgett, 1986). In Fig. 5. loss factor evolution vs frequency of NaCl water solution 0.5 M is shown to emphasize the two main loss mechanisms occurring (dipole polarization, ionic dissipation). One can easily verify that, for a given frequency and for a given concentration, the loss factor appears to be decreasing with temperature until the effect of the dipoles dominates and, then, increasing, when the effect of the charges prevails. For example, to a solution 0.1 M at 2.45 GHz, the loss factor ranges from 25 to 20 as the temperature increases from 0° C to 100°C, with a minimum of about 17 at a temperature of about 40°C (Barba & d'Amore, 2008). Temperature also affects viscosity medium properties increasing the mobility of charges.

4.2. Dielectric properties of fruits and vegetables

Thermal treatments are the most diffused processes applied in agro-foods manufacturing to obtain products with prolonged shelf-life and suitable to eating for enhanced digestibleness, flavours and rheological properties. Sterilization, pasteurization, pre-cooking and cooking, tempering of frozen foods and drying are the unit operations commonly applied (Metaxas, 1983; Schubert & Regier, 2005). Moreover, studies have been focused on the possibility of using electromagnetic energy to disinfest fruit harvests from insect pests (Wang et al., 2003) or to detect, by nondestructive investigation, the amount of moisture in materials by sensing the dielectric properties of the material (McKeown et al., 2011).

Despite the enormous industrial interest in food processing / characterization, the potentialities of microwave heating are not fully developed yet at industrial scale. Reasons of this delay include lacks of basic information on the dielectric properties of food and their relationships to microwave heating / material interaction characteristics and on equipment costs in a technology that has not been proven thoroughly reliable in large scale or long term uses (Ohlsson, 2000; Tang, Hao & Lau, 2002; Schubert & Regier 2005). However, world researches are currently developed on these subjects as proven by the hundreds of papers published each year on microwave / food / dielectric properties measurements topics and plants development.

Agro-foods show high interactions with the principal wave-frequencies used in industrial heating (915 MHz and 2.45 GHz), so they are raw materials suitable to be processed by microwave energy. In Figs. 6. and 7. dielectric constant and loss factor measurements of agro-foods (some kinds of fruits and vegetables) are reported. Accurate measurements have been carried out in fruits dielectric properties measurements due to the softer structure (pulp) that is optimal for a positioning under the coaxial probe. Conversely, in vegetables matrices measurements, air gaps, due to rough and fibrous surfaces, in some cases, strongly affected the performed measurements.

Both fruits and vegetables dielectric spectroscopies show that, due to moisture and soluble solids contents of agro-foods, their dielectric behavior are dominated by dipolar polarization

and ionic loss mechanisms. Indeed, dielectric constant profiles are characterized by typical monotonic trend and depressed values observed for of saline solution; loss factor signal shapes, especially at low frequency, highlight the predominance of an ionic dissipation mechanism. Soluble solids contents of agro-foods (measured by °Brix) can be referred to sugar, starch and mineral components. Hydration of sugar and starch molecules reduces dielectric constants; presence of minerals affects loss factors increasing the dissipative features. Moreover, relaxation time shifts to low frequencies.
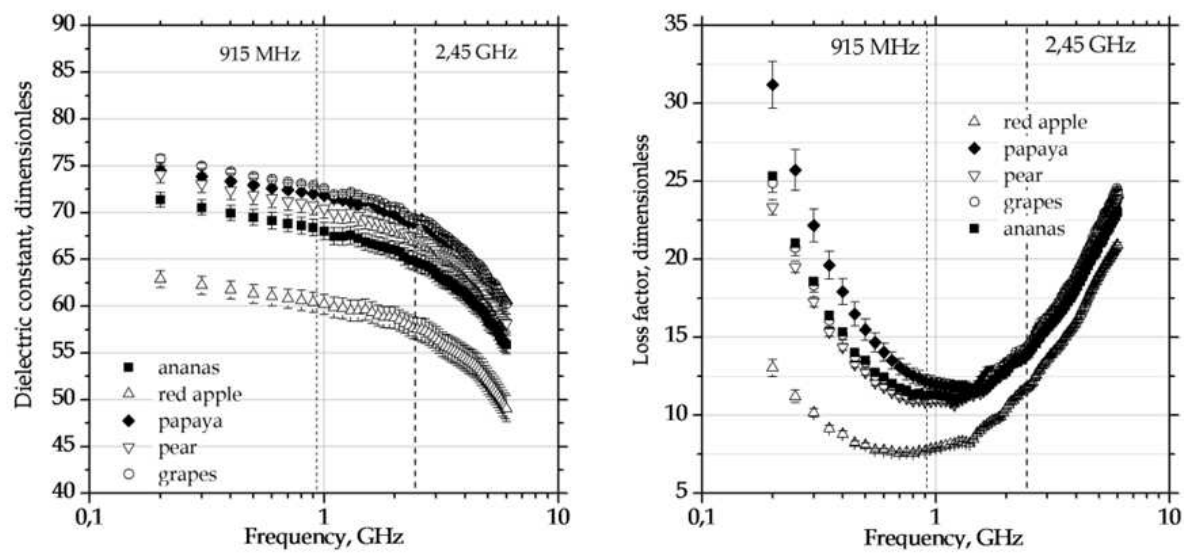

Figure 6. Dielectric spectroscopy of fruits (dielectric constant on left, loss factor on right; for fruits properties see Table 1.).
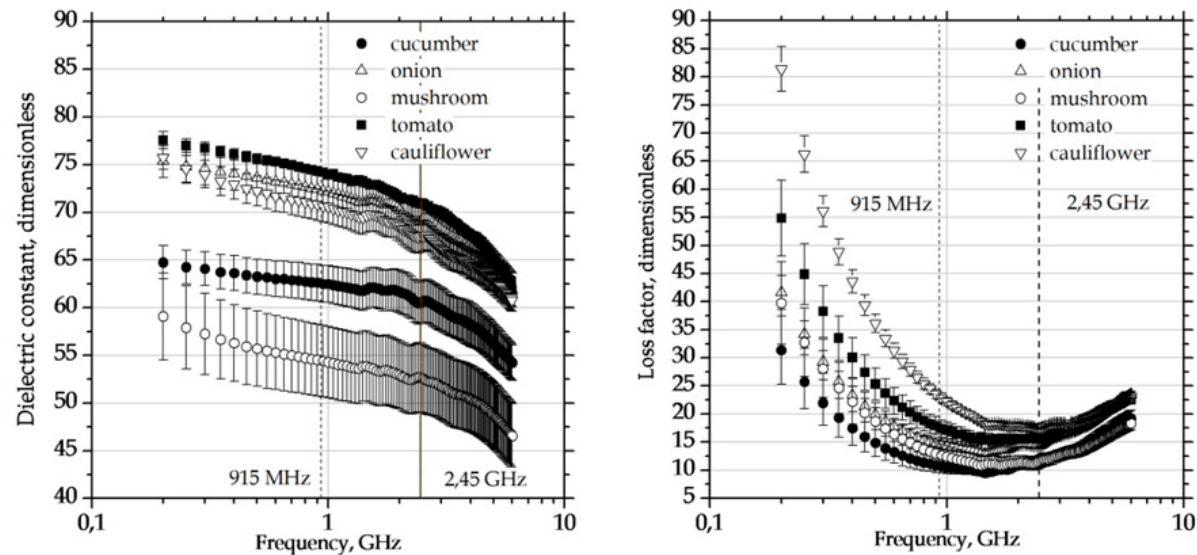

Figure 7. Dielectric spectroscopy of vegetables (dielectric constant on left, loss factor on right; for vegetables properties see Table 2.).

Fruit	Moisture content % w/w	°Brix %	Dielectric constant (2.45 GHz) ε′ ± SD	Loss factor (2.45 GHz)ε″± SD	Temperature °C
Ananas	86.00± 0.47	16	64.89 ± 0.99	13.98 ± 0.13	20
Banana	67.87±0.93	12.5	59.28 ± 0.58	17.72 ± 0.31	22
Black grapes	83.49± 0.22	16	66.11 ± 1.88	15.57 ± 0.91	20
Black plum	82.82±20	15	61.36 ± 5.53	14.38 ± 1.32	20
Cherry	71.22±5.61	12	70.08 ± 1.47	18.87 ± 0.36	22
Grapes	82.66±1.17	12.5	69.45 ± 0.09	14.35 ± 0.08	20
Green apple	82.37± 0.42	9	35.99 ± 0.86	7.06 ± 0.04	21
Kiwi	79.48±2.32	16	61.22 ± 0.12	15.72 ± 0.02	22
Lime	89.34± 0.34	7	59.20 ± 11.47	13.73 ± 3.10	20
Orange	83.54± 0.20	11	67.40 ± 0.17	14.37 ± 0.28	20
Papaya	81.62±3.47	12.5	69.00 ± 0.25	13.86 ± 0.28	22
Passion fruit	59.11± 5.14	13	58.13 ± 1.61	13.68 ± 1.61	22
Peach	87.73± 0.51	12.5	61.42 ± 14.07	11.07 ± 2.79	22
Pear	83.01±1.42	14	67.51 ± 1.05	14.16 ± 0.22	20
Red apple	87.02± 0.72	10	57.56 ± 1.18	11.72 ± 0.22	22
Strawberry	84.27±6.03	9	68.55 ± 2.05	12.40 ± 0.28	22

Table 1. Water content, °Brix, dielectric properties (at 2.45 GHz) of fruits.

Vegetable	Moisture content % w/w	°Brix %	Dielectric constant (2.45 GHz) ε′ ± SD	Loss factor (2.45 GHz)ε″± SD	Temperature °C
Cauliflower	84.90± 0.34	-	67.46 ± 1.66	17.42 ± 0.03	22
Cucumber	94.67± 0.09	3	60.49 ± 2.18	11.53 ± 0.21	22
Mushroom	91.90± 1.55	-	52.69 ± 3.63	11.50 ± 1.17	22
Onion	91.96± 1.60	-	69.06 ± 1.69	14.32 ± 0.43	22
Pepper	91.6± 4.30	7	59.10 ± 12.68	11.04 ± 2.48	21
Potato	69.50± 0.30	-	61.13 ± 5.41	16.63 ± 1.58	22
Ravanello	96.15± 1.95	-	68.88 ± 9.32	12.59 ± 1.94	22
Tomato	91.14± 0.22	9	70.87 ± 0.30	15.70 ± 0.50	21
Zucchini	95.50± 0.73	-	63.98 ± 3.67	15.02 ± 1.12	22

Table 2. Water content, °Brix, dielectric properties (at 2.45 GHz) of vegetables.

Temperature effects on dielectric properties of fruits matrices (banana: moisture content ~68%, °Brix=12.5; ananas: moisture content ~86%, °Brix=16) are shown in Figs. 8. and 9. As reported above, temperature affects dipolar dissipative mechanism because increases the molecular disorder and, thus, the reduction of dielectric properties values. Consequently, penetration depth increases (Fig. 9.). This latter behavior can assume a relevant role if bulk

heating are desired in large samples where an uniform temperature is not achieved due to the low penetration depth. Due to the influence of many parameters, it is difficult to develop a general predictive equation to accurately describe dielectric properties of foods. Eq. 9 summarizes the main factors that must be taken in account:

$$\varepsilon\left(f,T,M,\underline{\phi}\right)=\varepsilon'\left(f,T,M,\underline{\phi}\right)-ie''\left(f,T,M,\underline{\phi}\right) \tag{9}$$

where T is the temperature, M the moisture content, $\underline{\phi}$ is the vector of properties such as conductivity, heat capacity, molecular structure, density, size, crystallinity and many other physical properties of materials.
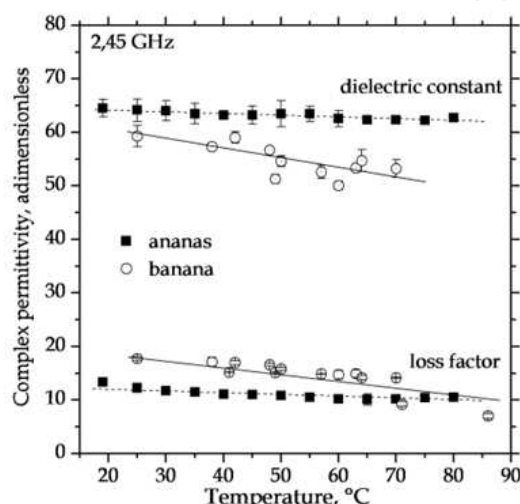

Figure 8. Dielectric properties of ananas and banana fruits *vs* temperature.
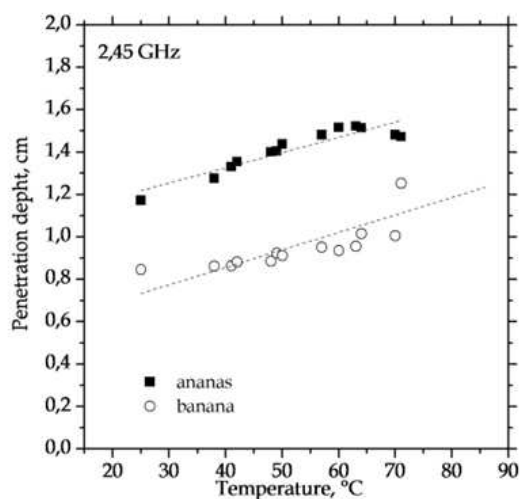

Figure 9. Penetration depths *vs* temperature calculated by eq. 4.

Under some conditions (i.e. given frequency for heating applications, constancy of materials properties etc…), empirical correlation are developed. In Sipahioglu & Barringer, 2003, empirical polynomial equations were proposed to estimate dielectric properties of agro foods:

vegetables:

$$\varepsilon' = -243.6 + 1.342 \cdot T + 4.593 \cdot M - 426.9 \cdot A + 376.5 \cdot A^2 - 0.01415 \cdot M \cdot T - 0.3151316.2 \cdot A \cdot T \quad (10)$$

$$\varepsilon'' = -100.02 - 0.1611 \cdot T + 0.001415 \cdot T^2 + 2.49 \cdot M - 378.9 \cdot A + 316.2 \cdot A^2 \quad (11)$$

fruits:

$$\varepsilon' = 22.12 + 0.2379 \cdot T + 0.5532 \cdot M - 0.0005134 \cdot T^2 - 0.003866 \cdot M \cdot T \quad (12)$$

$$\varepsilon'' = 33.41 - 0.4415 \cdot T + 0.001400 \cdot T^2 - 0.1746 \cdot M + 1.438 \cdot A + 0.001578 \cdot M \cdot T + 0.2289 \cdot A \cdot T \quad (13)$$

where T is the temperature, (°C), M and A are the moisture (% w/w dry basis) and the ash (%w/w dry basis) contents, respectively.

4.3. Dielectric properties of pharmaceutical aqueous mixtures

Interest in applications of microwave power (i.e. dielectric drying, curing) and related techniques for non-destructive, on-line moisture determination of wet powders and granules in pharmaceutical industry is relatively recent and not widespread. A non-consolidated know-how makes prudent industrial investments whereas, under a technical point of view, the need to have a uniform distribution of heat to avoid local overheating of the material, and, moreover, the possibility of a temperature uncontrolled increase are the main limiting factors (Heng et al., 2010; Barba et al., 2010a). In the last twenty years, mainly in Academic researches and in a few large-scale plants experiences, microwaves benefits have begun to capture attention. In particular, microwaves have been applied in modulating drug and excipient properties via specific material microwave interactions (Wong et al., 2002; Nurjaya & Wong, 2005; Auriemma et al., 2011); tested in drying operations of powder and granules (Hegedus & Pintye-Hodi, 2007; Loh et al., 2008); used in single-pot devices to carry out mixing, granulation and drying of pharmaceuticals in one vessel (Kelen et al., 2005; McMinn et al., 2005; Hegedus & Pintye-Hodi, 2007). Moreover, dielectric properties measurements of pharmaceutical powders wet mixtures are used to control moisture / solvent residues (Gradinarsky et al., 2006).

Once again, as in food industries, knowledge of the mechanisms and of the intensity of the interaction fields electromagnetic / pharmaceuticals is a fundamental step for any consolidation in equipment development and new processing methods.

In Fig. 10 dielectric properties of several common excipients (dry powders, some properties in Table 3.), at 2.45 GHz and room conditions, are reported (PVP, PolyVinyl-Pyrrolidone; CMC, Carboxy-Metil-Cellulose).

As can be easily seen, the excipients show very low dissipative features and, in turn, penetration depths assume high values (Fig. 11.). The effect of water content on dielectric properties of lactose and CMC distilled water mixtures is reported in Fig. 12 (at 2.45 GHz, room conditions).
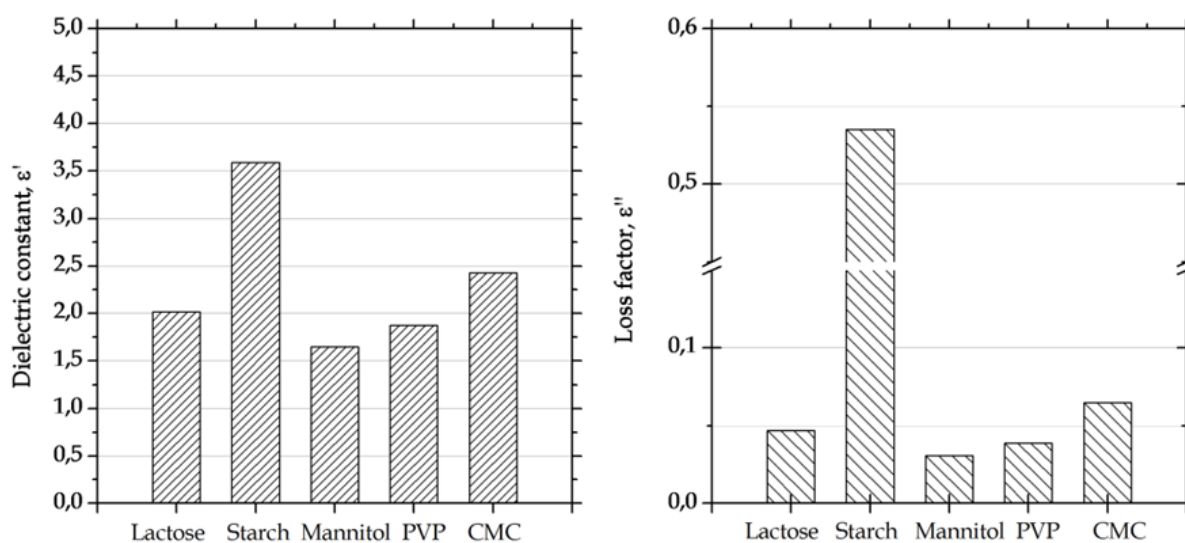
Figure 10. Dielectric properties of different pharmaceutical excipients (dielectric constant on left, loss factor on right) at 2.45 GHz, room temperature.
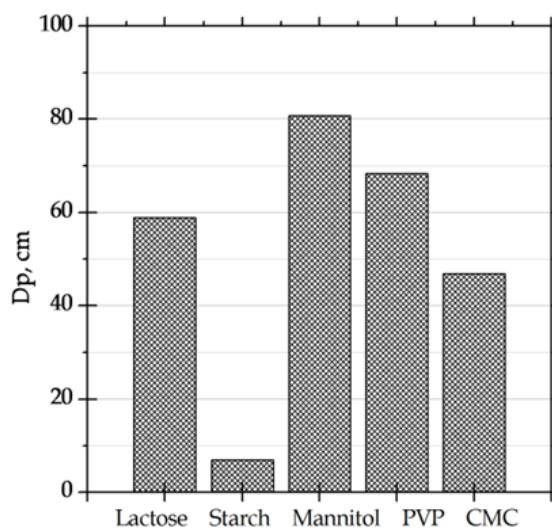

Figure 11. Penetration depth in different pharmaceutical excipients (water content at storage condition: lactose 0.5%; starch 9.4%; mannitol 0.19%; PVP 3.5%; CMC 6.5%) at 2.45 GHz, room temperature.

Excipient	Water content % w/w	D_p cm	Dielectric properties (2.45 GHz) ε' - ε''	Conductivity* µS/cm	Temperature °C
CMC	50%	0.50	35.6 – 23.2	4060.00	25
Lactose	50%	1.15	50.41-12.11	12.75	25
Mannitol	50%	1.43	56.9 - 10.3	6.03	25
PVP	50%	0.81	29.5 - 13.0	79.77	25
Starch	50%	1.42	53.9 -10.1	16.48	25
conductivity of excipient/distilled water at 0.02 g/L – distilled water conductivity: ~ 5.00 µS/cm					

Table 3. Excipient/water mixtures (50%w/w) data: dielectric properties, penetration depths, conductivities of diluted solutions.

In both kinds of mixtures, dielectric constant values show a monotone increasing trend as a function of water content, even if higher values are achieved in lactose mixtures rather than in CMC mixtures at equal water contents. Moreover, different critical moisture points are exhibited (M_c lactose~ 20%; M_c CMC~40%). This is due to the saline form of CMC powders (sodium salt) that gives ionic species in water medium and, indeed, the contribute of ionic dissipation mechanisms is observed in loss factor profiles. In particular, the effect of the ionic dissipation mechanism is clearly highlighted in the mixtures dielectric spectroscopies. In Figs. 13. and 14. dielectric properties of lactose and CMC water mixtures (50% w/w) as function of frequency and at different temperature are reported. Dielectric constant profiles show a decreasing trend with an opposite behavior at high temperatures. In lactose mixtures, a high temperature depresses the dielectric constant values because of molecular disorder, and in CMC mixtures a high temperature slightly increases the ionic species mobility. In loss factor profiles of CMC mixtures, the ionic dissipation mechanisms become very relevant at low frequency and increase with temperature because of an increased ionic conductivity as a result of viscosity reduction at high temperature. However, in loss factor profiles of lactose mixtures, temperature water behavior is kept unvaried.
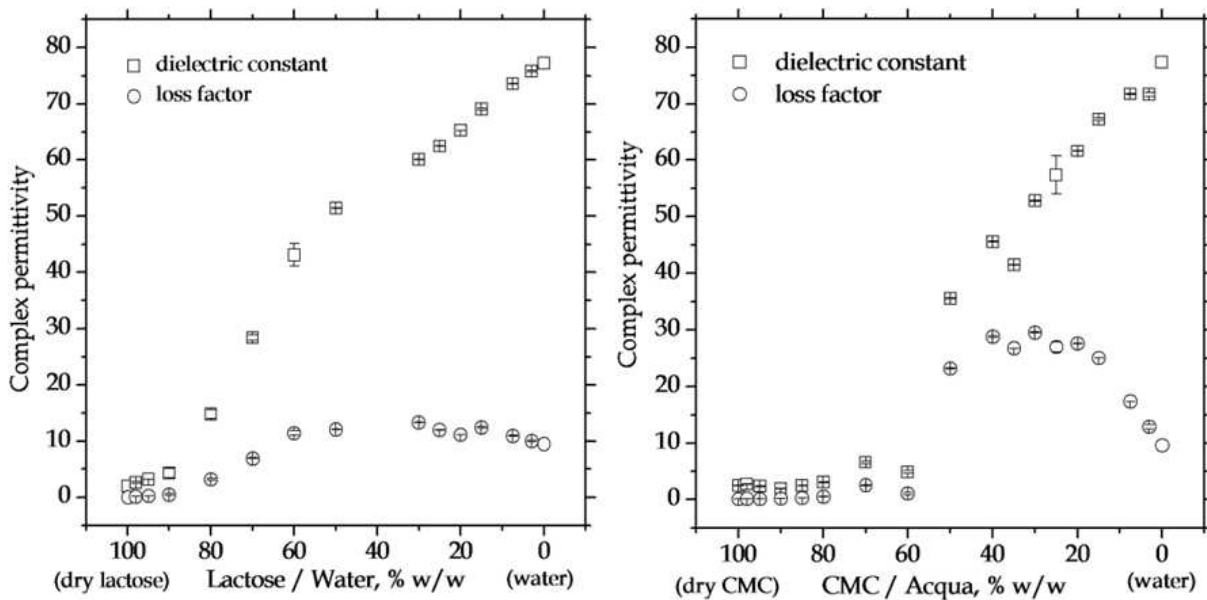

Figure 12. Dielectric properties of lactose / water mixtures (on the left) and of CMC / water mixtures (on the right) (at 2.45 GHz, room conditions).

4.4. Dielectric properties of biological tissues

Safe use of electromagnetic (EM) fields for medical purposes and, on the other hand, for the developing of protection systems from electronic devices leakages caused by industrial and domestic appliances, mobile antennas and so on, require to clarify the interaction between non-ionizing electromagnetic fields (EM) and living systems. Crucial point of investigations on any deleterious impact (overheated tissues) or induced benefit (diathermy, rewarming

from hypothermia and cancer treatments) is to quantify the specific absorption rate[4] (SAR) of the biological systems, i.e. to study their dielectric behavior during exposure to electromagnetic fields (Metaxas & Meredith, 1983; Adair & Petersen, 2002). Amount and distribution of the energy adsorbed in a biological system exposed to EM field is related to the internal electric and magnetic fields. As a wave penetrates in a biologic system, the electric field interacts at the various tissue interfaces resulting in a complex distribution of the local fields. These internal fields are related to a number of parameters including frequency, dielectric properties of the tissues, geometry and relative position from EM source. Currently, tools used to evaluate the interactions are either experimental measurements by thermographic or dielectric spectrometry methods (Guy, 1971, Gabriel C., 1996; Gabriel S., 1996a; Gabriel S., 1996b), and numerical simulation procedures (Foster & Adair, 2004).
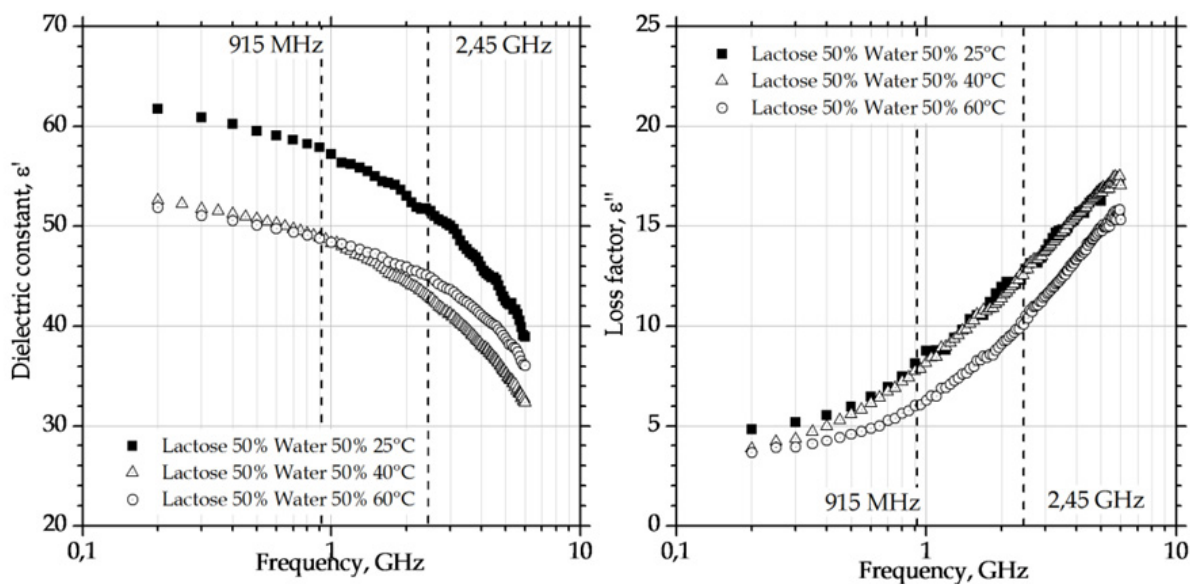

Figure 13. Dielectric spectroscopy of lactose water mixtures (1:1) at different temperatures.

Once more, dielectric properties measurements constitute a necessary step to estimate interaction and thus heating phenomena between fields and materials. In many experimental investigations, dielectric properties measurements of biological tissue are carried out in vivo on accessible parts of the body, ex vivo on fresh excised tissues and in tissue-equivalent materials (Barba et al., 2010b).

In Fig. 15. dielectric properties of bovine fresh excised tissues (liver and brain), measured by the open-end coaxial line method (snapshot of measurements in Fig. 16.), are shown. In general, due to the high moisture content (investigated tissues: liver 68-70%, brain 82-94%) and the saline species, biological tissues are highly receptive to microwave radiation.

---

[4] *SAR* of biological systems is defined as the time derivate of incremental energy (*dQ*) adsorbed by (dissipated in) an

incremental mass (*dm*) contained in a volume element (*dV*) with a given density ρ: $\mathrm{SAR} = \dfrac{\mathrm{d}}{\mathrm{dt}}\left(\dfrac{\mathrm{dQ}}{\mathrm{dm}}\right) = \dfrac{\mathrm{d}}{\mathrm{dt}}\left(\dfrac{\mathrm{dQ}}{\rho\mathrm{dV}}\right)$.
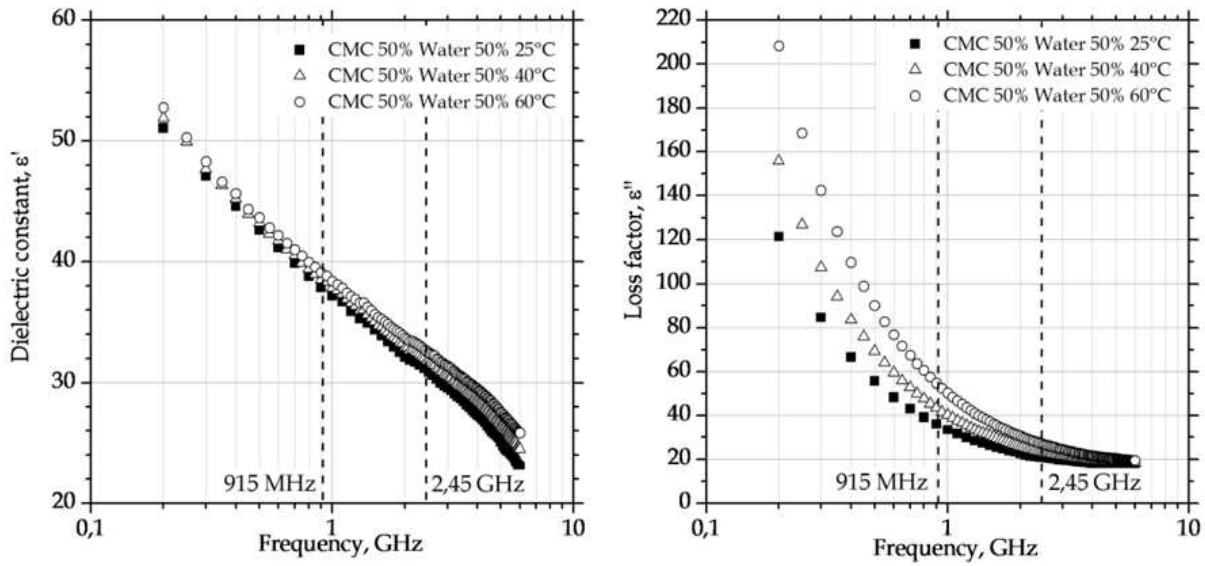
Figure 14. Dielectric spectroscopy of CMC water mixtures (1:1) at different temperatures.

In absence of phase changes, energy rate dissipation calculations could be performed starting from the classic equation of the power dissipation (eq. 2) using the values of measured dielectric properties and appropriately referring the power dissipation term (in eq. 14, Q is the dissipated energy amount [KJ]):

$$SAR = \frac{d}{dt}\left(\frac{dQ}{\rho dV}\right) = \frac{\dot{Q}_g}{\rho} = Cp \cdot \frac{dT}{dt} \tag{14}$$

It is worth noting that the application of eq. 2 is affected by the difficulty of knowing the electric field established in the tissue. On the other hand, temperature measurements (in eq. 14) correlated to dielectric properties (in eq. 2) allow an easy estimation of the electromagnetic field / tissue coupling intensity.
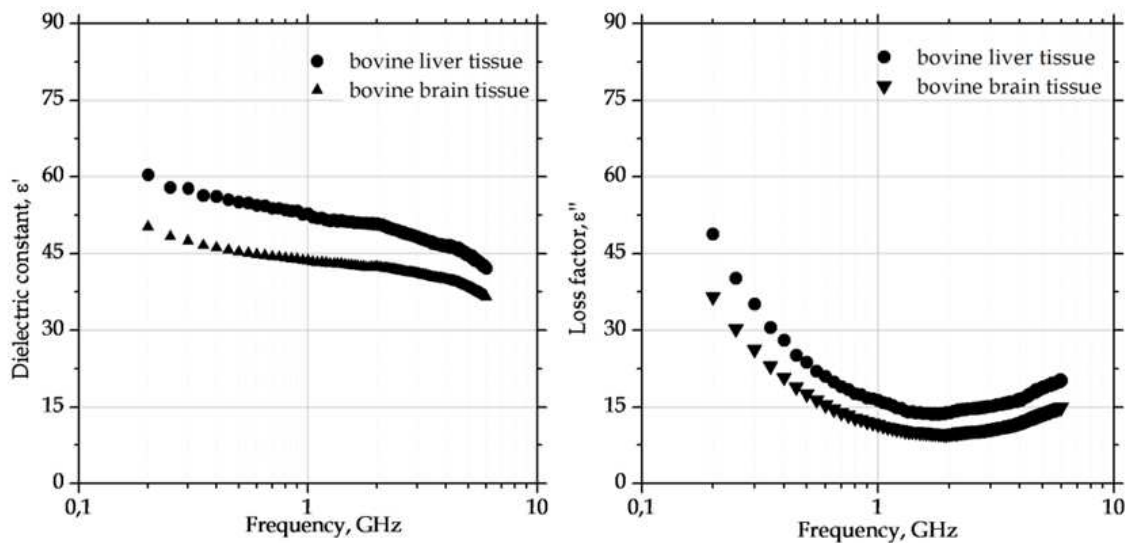

Figure 15. Dielectric constant and loss factor of liver and brain bovine tissues.
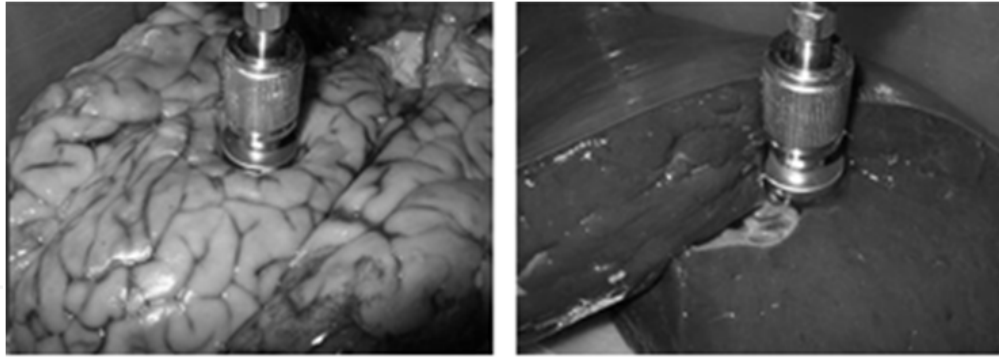
Figure 16. Snapshots of bovine tissues (brain and liver) dielectric properties measurements by open-end of the coaxial probe.

5. Modeling of microwave assisted processes

Modeling of microwave assisted processes can be classically approached starting from balance equations of momentum, energy and mass applied to a system under investigation and from solution of electromagnetic field distributions equations (Maxwell equations) (Acierno, Barba & d'Amore, 2008). With respect to the selected system a control volume, *V*, and a close surface, *S*, must be defined. Thus, the balance equations above cited, expressed through the general form of eq. 11 (Bird, Stewart and Lighfoot, 2002):

$$
\begin{Bmatrix} \text{rate of ACCumulation} \\ \text{of momentum, energy,} \\ \text{matter in the volume V} \end{Bmatrix} = \begin{Bmatrix} \text{INput flow rate} \\ \text{of momentum, energy,} \\ \text{matter through} \\ \text{the surface } S \end{Bmatrix} - \begin{Bmatrix} \text{OUTput flow rate} \\ \text{of momentu, energy,} \\ \text{matter through} \\ \text{the surface } S \end{Bmatrix} + \begin{Bmatrix} \text{GENeration rate} \\ \text{of momentum, energy,} \\ \text{matter} \\ \text{in the volume } V \end{Bmatrix} \tag{15}
$$

can be written. Applying the eq. 15 to the momentum ($\rho \underline{v}$), the equation of motion[5] is achieved:

$$
\frac{\partial}{\partial t}\rho\mathbf{v} = -\underline{\nabla}\cdot\underline{\underline{\phi}} + \rho\underline{\mathbf{g}} = -\nabla p - \underline{\nabla}\cdot\underline{\underline{\tau}} - \underline{\nabla}\cdot\rho\underline{\mathbf{v}}\underline{\mathbf{v}} + \rho\underline{\mathbf{g}} \tag{16}
$$

where *t* is the time variable [s], $\underline{\underline{\phi}}$ is the total flux of the momentum [N/m³], ρ is the density [kg/m³] and **g** is the gravity acceleration [m/s²]. The terms at the last member are the contributes of pressure ($\underline{\nabla}p$), viscosity ($\underline{\nabla}\cdot\underline{\underline{\tau}}$) and convective ($\underline{\nabla}\rho\underline{v}\underline{v}$) fluxes. The generation term in the momentum balance equation is due to the gravity per unit volume. Reorganizing eq. 16 introducing the substantial derivative and under some conditions

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[5] Notation: a scalar; $\underline{a}$ vector; $\underline{\underline{a}}$ tensor; $\cdot$ scalar product; x vectorial product; $\underline{\nabla}a$ gradient; $\underline{\nabla}\cdot\underline{a}$ divergence: ∇^2 a Laplacian.

(density as a function of temperature according to the Boussinesq approximation, with β volumetric expansivity coefficient; Newtonian flux, with μ dynamic viscosity [Pa·s]) the equation of motion becomes:

$$\rho_0 \frac{D}{Dt}\underline{\mathbf{v}} = \left(-\nabla p + \rho_0 \underline{\mathbf{g}}\right) - \mu \nabla^2 \underline{\mathbf{v}} - \rho_0 \underline{\mathbf{g}}\beta\left(T - T_0\right) \tag{17}$$

Eq. 17 is therefore the most useful form of momentum balance equation; it is solved introducing initial and boundary conditions and its solution represents the velocity field $\underline{v}$(t, $\underline{x}$), where $\underline{x}$ is the spatial vector.

Applying the eq. 15 to the energy $\rho\left(\hat{U} + \frac{1}{2}v^2\right)$, the equation of energy is achieved:

$$\frac{\partial}{\partial t}\rho\left(\hat{U} + \tfrac{1}{2}v^2\right) = -\underline{\nabla}\cdot\underline{\mathbf{e}} + \rho\underline{\mathbf{v}}\cdot\underline{\mathbf{g}} + GEN =$$
$$= -\underline{\nabla}\cdot\rho\left(\hat{U} + \tfrac{1}{2}v^2\right)\underline{\mathbf{v}} - \underline{\nabla}\cdot\underline{\mathbf{q}} - \underline{\nabla}\cdot\left(\underline{\underline{\pi}}\cdot\underline{\mathbf{v}}\right) + \rho\underline{\mathbf{v}}\cdot\underline{\mathbf{g}} + GEN \tag{18}$$

Eq. 18 is the energy equation written using the concept of the total flow of energy($\underline{\nabla}\cdot\underline{e}$), and making explicit the terms due to convection $\underline{\nabla}\cdot\rho\left(\hat{U} + \frac{1}{2}v^2\right)\underline{\mathbf{v}}$, conduction ($\underline{\nabla}\cdot\underline{q}$) and viscous phenomena ($\underline{\nabla}\cdot(\underline{\pi}\cdot\underline{v})$, where $\underline{\pi}$ accounts for pressure and viscous stress contributions to $\underline{\phi}$). The term ($\rho\underline{v}\cdot\underline{g}$) takes into account the generation of energy due to the motion against gravity (potential energy); other energy generation phenomena are included in the term *GEN* and they can refer to chemical / nuclear reactions, heat dissipation due to external causes (electrical, magnetic). Reorganizing eq. 18 introducing the substantial derivative and under some conditions (viscous stress is relevant only for high shear rates; processes at constant pressure, material density constant or slightly variable; Fourier conductive flux, with *K* thermal conductivity [W/m·K]), the equation of energy can be express by:

$$\rho\hat{C}_p\frac{D}{Dt}T = -K\nabla^2 T + \sum_i \Delta H_i r_i + \sum_j \dot{Q}_j \tag{19}$$

where $\Sigma_i\, \Delta H_i r_i$ and $\Sigma_j Q_j$ are the summations of generation terms due to phase changes/ chemical reactions (ΔH_i, latent heat, r_i volumetric rate) and to supplied/subtracted heat due to external sources (Q_j volumetric heat rate). The solution of eq. 19, performed after initial and boundary conditions definition, gives the temperature field T(t, $\underline{x}$).

Applying the eq. 15 to the mass ($\varrho_A = \rho\omega_A$) the mass equation is achieved:

$$\frac{\partial}{\partial t}\rho\omega_A = -\underline{\nabla}\cdot\underline{\mathbf{n}}_A + r_A = -\underline{\nabla}\cdot\rho\omega_A\underline{\mathbf{v}} - \underline{\nabla}\cdot\underline{\mathbf{j}}_A + r_A \tag{20}$$

where ω_A is the *A* component mass fraction. Eq. 20 is the mass equation, written using the concept of the total matter flow ($\underline{\nabla}\cdot\underline{n}_A$) and making explicit the terms due to convection ($\underline{\nabla}\cdot\rho\omega_A\underline{v}$) and diffusion ($\underline{\nabla}\cdot\underline{j}_A$) phenomena. The generation term r_A expresses the volumetric

rate of the *A* component appearance/disappearance. The solution of eq. 20, performed after initial an boundary conditions definition, gives the fraction mass field, ω_A(t, $\underline{x}$). Under some condition (binary system with constant density; Fick diffusive flux, with D_{AB} diffusivity [m^2/s]), the eq. 20 can be express by:

$$\frac{\partial}{\partial t}\rho_A + \underline{\mathbf{v}} \cdot \underline{\nabla}\rho_A = D_{AB}\nabla^2\rho_A + r_A \tag{21}$$

Maxwell equations in the frequency domain can be written by (Metaxas and Meredith, 1983; Chan & Reader, 2000; Meredith, 2006):

$$\begin{cases} \underline{\nabla} \times \underline{E}\left(\underline{x},\omega\right) = -j\omega\underline{B}\left(\underline{x},\omega\right) - \underline{J}_m\left(\underline{x},\omega\right) - \underline{J}_{m0}\left(\underline{x},\omega\right) \\ \underline{\nabla} \times \underline{H}\left(\underline{x},\omega\right) = j\omega\underline{D}\left(\underline{x},\omega\right) + \underline{J}\left(\underline{x},\omega\right) + \underline{J}_0\left(\underline{x},\omega\right) \\ \underline{\nabla} \cdot \underline{D}\left(\underline{x},\omega\right) = \rho\left(\underline{x},\omega\right) + \rho_0\left(\underline{x},\omega\right) \\ \underline{\nabla} \cdot \underline{B}\left(x,\omega\right) = \rho_m\left(\underline{x},\omega\right) + \rho_{m0}\left(\underline{x},\omega\right) \end{cases} \tag{22}$$

where $\underline{x}$ is, as usual, the position vector, ω is angular frequency (it takes in account the time variable) and where $\underline{E}$($\underline{x}$, ω), $\underline{H}$($\underline{x}$, ω) $\underline{D}$($\underline{x}$, ω) $\underline{B}$($\underline{x}$, ω) are le solutions for the electric field [V/m], magnetic field [A/m], induction electric field [C/m^2] induction magnetic fields [Wb/m^2] respectively. The other terms in eq. 22 are referred to the sources of the electromagnetic phenomena: $\underline{J}$($\underline{x}$, ω) current electric density [A/m^2]; $\underline{J}_m$($\underline{x}$, ω) magnetic current density [V/m^2]; c($\underline{x}$, ω) electric charge density [C/m^3]; ρ_m($\underline{x}$, ω) magnetic charge density [Wb/m^3]; $\underline{J}_0$($\underline{x}$, ω) current electric density (external sources) [A/m^2]; $\underline{J}_{m0}$($\underline{x}$, ω) magnetic current density (external sources) [V/m^2]; ρ_0($\underline{x}$, ω) electric charge density (external sources) [C/m^3]; ρ_{m0}($\underline{x}$, ω) magnetic charge density (external sources) [Wb/m^3].

Thus, the generic problem of electromagnetism, described by eq. 22 consists in solving a system of differential equations with four unknowns vector functions (the fields above defined). In general, to reduce the complexity of the problem the fields are linked to the inductions by relations (which are generally non-differential) dependent on the material in which the phenomena occur. These equations are called constitutive relations. Of great practical importance is the case of the media isotropic and temporally non-dispersive, for which it can be written:

$$\begin{cases} \underline{D}\left(\underline{x},\omega\right) = \varepsilon\left(\underline{x},\omega\right)\underline{E}\left(\underline{x},\omega\right) \\ \underline{B}\left(\underline{x},\omega\right) = \mu\left(\underline{x},\omega\right)\underline{H}\left(\underline{x},\omega\right) \end{cases} \tag{23}$$

where the functions ε($\underline{x}$, ω) and μ($\underline{x}$, ω) are the complex permittivity and permeability, respectively. Their values can be achieved from direct measurements using the techniques discussed in previous paragraphs.

Summarizing, description of a process in which the material interacts with microwaves, requires the solution of the equations of change of momentum, energy and matter, in addition to the solution of the equations of the electromagnetic field (Maxwell's equations).

These two classes of equations are related through the material constants (viscosity, density, specific heat, thermal diffusivity, electric permittivity and magnetic permeability). In addition, crucial point in the problems of dielectric heating, is the evaluation of the heat generation term that appears in the energy balance equation due to dissipation of the microwave energy in the material. It is well evident that this is a very challenging task, dealing with partial differential equations whose solutions may show a functional dependency from four independent variables (time and three spatial coordinates). To make less burdensome the calculation procedures, problems can be suitably simplified prior to their resolution. The three types of approximations more broadly applied are (Bird, Stewart and Lighfoot, 2002):

i.   postulates, in which a tentative guess is made as to the form of the solution (as an example: the temperature field T(t, x, y, z) can be expressed by T(t, x));
ii.   assumptions, in which one can eliminate some physical phenomena or effects by discarding terms or assuming physical properties to be constant;
iii. search for an asymptotic solution, in which one can obtain only a portion of the entire mathematical solution.

In balance equations, the phenomena that are not dominant can be neglected and/or material features can be kept as constant value. In the description of electromagnetic waves propagation in material media, simplified ways to describe the resolution of Maxwell's equations are constituted by the law of Lambert and Beer and the theories of waveguides and reverberant cavities. In the first case, it is possible to image electromagnetic waves as plane waves, whose intensity exponentially decreases along the direction of penetration (z) of the body with the following mathematical structure:

$$E(z) = E_0 \exp\left(-\frac{z}{D_p}\right) = E_0 \exp\left(-\frac{2\pi f}{c}\frac{\varepsilon''}{\sqrt{\varepsilon'}}z\right) \tag{24}$$

where z is the coordinate in the direction of propagation, E_0 is the intensity of the incident field; and where the D_p parameter depends from material dielectric properties (eq. 4).

In the second case it is possible to apply some simplifications of the Maxwell equations, consistent with the propagation of electromagnetic waves in isotropic systems, without electromagnetic field sources and structured as "pipes" (waveguides) or "closed cavity" (the reverberant cavity) made of conductive materials. Each of these solutions is a "mode" of propagation of the microwaves in the guides or in the cavities. The analytical forms of descriptive ways have been obtained and are summarized in electromagnetic handbooks. The modes of propagation are characterized by having Transverse Electric field (TE modes) or Transverse Magnetic field (TM modes), where the adjective transverse indicates field orthogonality to the axis of the guide or to the major axis of the cavity (Metaxas and Meredith, 1983; Chan & Reader, 2000).

If attention is focused on the mass and heat transfer phenomena occurring through wet materials (foods, pharmaceuticals) undergoing to a microwave assisted drying process, a

simplified modeling of the overall process can be developed as follows. Starting from eq. 17, 19, and 21 and under the approximations:

1. no motion in the solid phase occurs, $\underline{v} = \underline{0}$;
2. the functions of interest (residual moisture, M, and temperature, T, profiles) only depend on time (t) and depth (z), i.e. $T = T(t, z)$ and $M = M(t, z)$;
3. liquid water does not diffuse in the solid matrix, $D_{AB} = 0$;
4. the following physical characteristics of the materials are considered constant: density (ρ), specific heat (Cp) and thermal conductivity (K) of the solid, latent heat of evaporation (ΔH_M) of the water;
5. microwaves (of a given frequency) propagate as a plane wave partially absorbed by the material according to the law of Lambert and Beer;

the variation equations of temperature and mass become:

$$\rho C_p \frac{\partial}{\partial t} T = -K \frac{\partial^2}{\partial z^2} T + \Delta H_M r_M + \dot{Q}_g \tag{25}$$

$$\frac{\partial}{\partial t} M = -r_M \tag{26}$$

The two mono-dimensional transient equations are coupled by the volumetric rate of water disappearance r_M. To solve the two partial differential equations, the following initial and boundary conditions can be chosen:

$$\textit{Initial Conditions}: \qquad @t = 0, \forall z \qquad T(0, z) = T_0, M(0, z) = M_0 \tag{27}$$

$$\textit{Boundary Conditions}: \qquad @z = 0, \forall t \qquad -K \frac{\partial T}{\partial z} = h\left(T\big|_{z=0} - T_\infty\right) \tag{28}$$

$$@z = L, \forall t \qquad \frac{\partial T}{\partial z} = 0 \tag{29}$$

where $h(T_{z=0} - T_\infty)$ is the convective flux at the material surface, L is the thickness of the irradiated system. The energy dissipation due to microwaves is taken into account in the term $\dot{Q}_g$ of eq. 25, where the electric field strength is described using eqq. 2, 4 and 24 (summarized in eq. 30) with the assumption that microwaves propagate as a plane wave:

$$\dot{Q}_g = \frac{1}{2} \omega \varepsilon_o \varepsilon''(T, M) \left| E_0 \exp\left(-\frac{2\pi f}{c} \frac{\varepsilon''(T, M)}{\sqrt{\varepsilon'(T, M)}} z \right) \right|^2 \tag{30}$$

Finally, dielectric properties correlation $\varepsilon(T, M) = \varepsilon(T(t,z), M(t,z))$ values must be known. At last, as one can be seen, experimental measurements of dielectric properties do play a key role. Other applications are reported in Barba et al., 2004, Acierno et al., 2008, Barba et al., 2012, Malafronte et al., 2012.

6. Conclusion

The main remarks of this chapter can be summarized as follows.

i.   Microwave heating can be a powerful tool for thermal treatments because many benefits can be achieved but its successful use is directly associated with the dielectric properties of irradiated materials.
ii.   In microwave assisted processes, the knowledge of dielectric properties and of parameters that affect their values allows to predict and provide desired heating partners in materials avoiding overheating and misheating.
iii. To measure dielectric properties, different techniques are available; their applicability are affected by several parameters such as intrinsic nature of materials under investigation (high or low dissipative features, solid or liquid state, magnetic or corrosive material, etc…); geometrical shape (thin film, thick solids, etc…); environmental conditions (high temperature, etc…). The open-ended coaxial-probe method is suitable to characterize many materials such as foods, pharmaceuticals and biological tissues.
iv.   Modelling of microwave assisted processes can be approached by the solution of balance of heat, mass and momentum equations together with the solution of the electromagnetic field distributions equations. Complexity of the mathematical solutions of the coupled equations in their general form may be overcome taking advantage of the approximations possible when adapting the general problem to a peculiar application, with known geometry or properties, or predominant terms.

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7. References

Acierno, D., Barba, A.A., & d'Amore M. (2008). I Fenomeni di Trasporto, In: *Il riscaldamento a microonde. Principi ed Applicazioni*, pp. (53-75), Pitagora Editrice, ISBN 9-788837-116996, Bologna, IT

Adair, E.R., & Petersen, R.C. (2002). Biological Effects of Radio-Frequency/Microwave Radiation. *IEEE Transactions on Microwave Theory and Techniques*, Vol. 50, No. 3, (March 2002), pp. (953-962), ISSN 0018-9480

Al-Harahsheh, M.,& Kingman, S.W. (2004). Microwave-assisted leaching—a review. *Hydrometallurgy*, Vol. 7, No. 3-4, pp. (189–203), ISSN 0304-386X

Auriemma, G., Del Gaudio, P., Barba, A. A., d'Amore, M., & Aquino, R.P. (2011). A combined technique based on prilling and microwave assisted treatments for the production of ketoprofen controlled release dosage forms. *International Journal of Pharmaceutics* Vol. 415, No. 1-2, pp. (196–205), ISSN 0378-5173

Barba, A.A., Acierno D., & d'Amore M. (2012). Use of microwaves for in-situ removal of pollutant compounds from solid matrices. *Journal of Hazardous Materials*, Vol. 207-208, No. March, pp.(128-135), ISSN 0304-3894

Barba, A.A., & d'Amore M. (2008). Applicazioni delle microonde nel settore agroalimentare, In: *Il riscaldamento a microonde. Principi ed Applicazioni,* pp. (269-295), Pitagora Editrice, ISBN 9-788837-116996, Bologna, IT

Barba, A.A., Guidotti, C., & d'Amore M. (2010). Processi intensificati in ambito farmaceutico: le applicazioni di potenza delle microonde, *Notiziario Chimico-Farmaceutico*, Febb. 2010, pp. (68-71), ISSN 0393-3733- 6.

Barba, A.A., Notari A., & d'Amore, M. (2010). Tissue-equivalent materials in studying interactions between non-ionizing radiation and living systems, *Proceedings of XVIII RiNEm*, ISBN 978-88-905261-0-7 Benevento, Italy, September 6th–10th 2010

Barba, A.A., d'Amore, M., & Acierno, D. (2004). Heat Transfer Phenomena During Processing Materials with Microwave Energy. *Heat and Mass Transfer*, Vol. 40; No. 5, pp. (413-420), ISSN 0947-7411

Bird, R.B., Stewart, W.E., & Lightfoot, E.N. (2002). *Transport Phenomena* (2nd Ed.) John Wiley & Sons, ISBN 0-471-36474-6, Danvers, MA-USA

Chan, C.T.T.V. & Reader, H.C. (2000). *Understanding Microwave Heating Cavities*, Artech House Inc., ISBN 158053094-X Norwood, MA-USA

Coulson & Richardson's, Chemical Engineering (2002). Product Design and Process Intensification, In: *Particle Technology & Separation Processes*, Richardson, J.F.; Harker, J.H.; Backhurst, J.R, 5th Ed., Vol. 2, pp. (1104-1135) Elsevier Butterworth Heinemann, ISBN 978-0-7506-4445-7, NL

Foster, K.R., & Adair, E.R. (2004). Modeling thermal responses in human subjects following extended exposure to radiofrequency Energy. *BioMedical Engineering OnLine*, Vol. 3:4, No. February, pp. (1-7)

Gabriel, C., Gabriel, S., & Corthout, E. (1996). The dielectric properties of biological tissues: I. Literature survey. *Physics in Medicine and Biology*, Vol. 41, No. 11, pp. (2231–2249) ISSN 0031-9155

Gabriel, S., Lau, R.W., & Gabriel, C. (1996). The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. *Physics in Medicine and Biology*, Vol. 41, No. 11 , pp. (2251–2269) ISSN 0031-9155

Gabriel, S., Lau, R.W., & Gabriel, C. (1996). The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues. *Physics in Medicine and Biology*, Vol. 41, No. 11, pp. (2271–2293) ISSN 0031-9155

Gradinarsky, L., Brage, H., Lagerholm B., Björn, I.N., & Folestad, S. (2006). In situ monitoring and control of moisture content in pharmaceutical powder processes using an open-ended coaxial probe. *Measurement Science and Technology*, Vol. 17, pp. (1847-1853) ISSN 0957-0233

Guy, A.W. (1971). Analyses of electromagnetic fields induced in biological tissues by Thermographic Studies on Equivalent Phantom Models. *IEEE Transaction on Microwave Theory and Techniques*, Vol. mtt-19, No. 2, pp. (205 - 214), ISSN: 0018-9480

Hegedus, A., & Pintye-Hodi, K. (2007). Comparison of the effects of different drying techniques on properties of granules and tablets made on a production scale. *International Journal of Pharmaceutics*, Vol. 330, No. 1-2, pp. (99–104) ISSN: 0378-5173

Heng, P.W.S., Loh, Z.H., Liew, C.V., & Lee, C.C. (2010). Dielectric properties of pharmaceutical materials relevant to microwave processing: effects of field frequency, material density, and moisture content. *Journal of Pharmaceutical Sciences*, Vol. 99, No. 2, pp. (941–957), ISSN 1520-6017

Kelen, A., Ress, S., Pallai E., & Pintye-Hòdi, K. (2006). Mapping of temperature distribution in pharmaceutical microwave vacuum drying. *Powder Technology*, Vol. 162, pp. (133-137) ISSN 0032-5910

Kraszewski, A. (1996). *Microwave Aquametry Electromagnetic Wave Interaction with Water-Containing Materials*, IEEE Press, ISBN 0-7803-1146-9, New York, USA .

Kulkarni, P.S., Crespo, J.G., & Afonso, C.A.M. (2008). Dioxins sources and current remediation technologies—a review. *Environment International*, Vol. 34, No. 1, pp. (139–153), ISSN 0160-4120

Loh, Z.H., Liew, C.V., Lee, C.C., & Heng, P.W.S. (2008). Microwave-assisted drying of pharmaceutical granules and its impact on drug stability. *International Journal of Pharmaceutics*,Vol. 359, No. 1-2, pp. (53–62), ISSN: 0378-5173

Malafronte, L., Lamberti G., Barba A.A., Raaholt B., Holtz E., & Ahrné, L. (2012), Combined convective and microwave assisted drying: experiments and modeling. *Journal of Food Engineering,* Vol. 112, No. 4, pp. (304–312) ISSN 0260-8774

McKeown, M.S., Trabelsi S., Tollner, E.W., & Nelson S.O. (2012). Dielectric spectroscopy measurements for moisture prediction in Vidalia onions. *Journal of Food Engineering*, Vol. 111, No. 3, pp. (505–510), ISSN 0260-8774

McMinn, W.A.M., McLoughlin T.C.M., & Magee, T.R.A. (2005). Microwave–convective drying characteristics of pharmaceutical powders. *Powder Technology*, Vol. 153, No. 1, pp. (23– 33), ISSN 0032-5910

Meredith, R.J. (1998). *Engineers' Handbook of Industrial Microwave Heating*, IEE Power Engineering, ISBN-10: 0852969163, London, UK

Metaxas, A.C. & Meredith, R.J. (1983). *Industrial Microwave Heating*, Peter Peregrinus Ltd., ISBN 0906048893, London, UK

Mudgett, R.E. (1986). Electrical properties of foods, In: *Engineering properties of foods*, Rao M.A. and Rizvi S.S.H., Eds., Marcell Dekker Inc., ISBN 0-8247-7526-0, pp. (49-87), New York, 1986

Nurjaya, S, & Wong T.W.(2005). Effects of microwave on drug release properties of matrices of pectin. *Carbohydrate Polymer,* Vol. 62, No. , pp. (245-257) ISSN 0144-8617

Olhsson, T. (2000). Minimal processing of foods with thermal methods, In: *Innovations in Food Processing,* Barbosa-Canovas G.V., Gould G.W., Eds., pp. (141-148) Technomic Inc., ISBN 1-56676-782-2, Lancaster, PA, USA

Remya, N., & Lin, J.G. (2011). Current status of microwave application in wastewater treatment—a review. *Chemical Engineering Journal*, Vol. 166, No. 3, pp. (797–813), ISSN 1385-8947

Schubert, H., & Regier M. (2005). *The Microwave Processing of Foods*, CRC Press Woodhead Publishing, ISBN 978-1-85573-964-2 Boca Raton, FL, USA

Sipahioglu, O., & Barringer, S.A. (2003). Dielectric Properties of Vegetables and Fruits as a Function of Temperature, Ash, and Moisture Content. *Journal of Food Science*, Vol. 68, No. 1, pp. (234–239), ISSN 1750-3841

Stankiewicz, A. & Moulijn J. (2004). *Re-engineering the chemical processing plant: process intensification*, M. Dekker, ISBN 0824743024 9780824743024 New York, USA

Tang, J., Hao, F., & Lau, M. (2002). Microwave Heating in Food Processing, In: *Advanced Bio-processing Engineering*, X.H. Yang and J. Tang Eds., pp. (1-44), Word Scientific Ltd., ISBN 981-02-4696-X, Singapore

Wang, S., Tang, J., Johnson, J.A., Mitcham, E., Hansen, J.D., Hallman, G., Drake, S.R., & Wang, Y. (2003). Dielectric Properties of Fruits and Insect Pests as related to Radio Frequency and Microwave Treatments. *Biosystems Engineering*, Vol. 85, No. 2, pp. (201–212), ISSN 1537-5110

Wong, T.W., Chan L.W., & Kho, S.B., & Heng, P.W.S. (2002). Design of controlled release solid dosage forms of alginate and chitosan using microwave. *Journal of Control Release*, Vol. 84, No. 3, pp. (99-114), ISSN 0168-3659

Zhou, J., Shi, C., Mei, B., Yuan, R., & Fu, Z. (2003). Research on the technology and the mechanical properties of the microwave processing of polymer. *Journal of Materials Processing Technology*, Vol. 137, No. 1-3, pp. (156–158), ISSN 0924-0136