For Conceptual Understanding of Microwave Heating

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Microwave dielectric heating is now commonly employed in domestic purposes as well as in laboratory and industrial practices.   In industrial practice it is used for processing food and other materials like ceramics, rubbers and plastics [1-2].   There are two or three advantages claimed for microwave heating namely, quick heating, safe and energy efficient.   How does one derive these advantages in dielectric heating?   The interaction of electromagnetic waves with mater is normally characterized by various possible interactions like excitation and emission.   Among these two parameters the parameters of relevance for this topic are the complex dielectric permittivity, ε, and complex magnetic susceptibility, μ, [3].   However the complex magnetic susceptibility may not be important for biological and agricultural materials since they do not exhibit any magnetic susceptibility.   Thus dielectric heating is normally induced by the electric field through dipolar rotation or ionic conduction.

When a dipole is exposed to an electric field, the dipole will try to align itself with the corresponding field polarity. When the applied electric field is rapidly changing, the dipolar molecule try to realign to the new direction (possibly also rapidly) at certain frequency related to the frequency of the electric field and this results in the dipole spinning around. In their attempt to align themselves the dipoles rasp with each other causing friction and subsequent heating.

In ionic conductance, changed ions oscillate through the solution under the influence of the applied electric field.   As the applied electric field direction changes the ions also change direction.   The interaction phenomenon induced between electromagnetic waves and the dielectric substance can be considered in terms of two parameters, namely the dielectric constant ,ε' – representing the storage of electromagnetic energy in the material and the dielectric loss factor, ε" the thermal conversion of the electromagnetic energy.

These two quantities is related to permittivity by the equation [4]

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (1)$$

Now, one should know how dielectric permittivity depends on frequency and temperature.   Frequency dependence for polar substances can be expressed by Debye's equation [5] or for not pure polar substances by the Cole-cole equation [6].   At low frequencies, the electric field is reversed at a slower speed, which provides more time for the molecules to align and store the charge in the dipoles, increasing ε'. As frequency increases, the field oscillation is rapid, not allowing the molecules to stabilize in the field and store energy thus decreasing ε'. The so called relaxation spectrum depends on various material parameters such as temperature, molecular weight and concentration.

The two equations namely Debye and Cole-Cole equation is valid only for pure substances, it has been attempted various mixing rules to calculate the dielectric properties of heterogeneous and homogeneous mixtures like the Landau-Lifshit-Looyenga equation [7,-9]. These mixing equations can be applied to non-interacting and powdered mixtures and cannot be applied to liquids [10]. In the case of reacting mixtures, the volume, density, temperature and concentration of reactants and products as well as that of intermediate products should be accounted for, since these parameters change as the reaction proceeds. The method of analytically calculating the dielectric properties of reacting mixtures at various temperatures is difficult as too many parameters have to be taken into account. This attempt may be possible to a limited extent for simple cases only.

Another factor that can be used to explain the dielectric heating is the loss tangent or loss angle δ that is the ratio of ε" to ε', this parameter depends on the relaxation time τ. The torque exerted by the electric field induces rotation in the polar molecules, but the rate at which molecules orient could be slower compared to the applied electric field. The delay between the electromagnetic stimulation and molecule response example τ is responsible for ε". An increase in ε" is observed when the equation $\omega = 1/\tau$ is satisfied where $\omega = 2\pi/T$ where T is the oscillation period. When the solvents τ Is higher , then there is an increase in loss tangent with temperature resulting in higher rate of conversion of electromagnetic energy into thermal energy [11]. This is the reason for localized super heating in organic solvents [11]. If τ is many times greater than the period T, Polarization is barely able to develop gand ε" is very small. At low frequencies where τ is smaller than T, The polarization follows the field and ε" is also small because the number of reorientations per unit time is small.

Relaxation time is temperature dependent and decreases as the temperature is increased, it is also viscosity dependent [2] according t o the equation

$$T = (4\pi r^3 \mu)/k_b Temp$$

Where r is gyration radius of the molecule (m), μ is the viscosity of solution (Pa.s), Temp is absolute temperature (K) and k_b is Boltzmann's constant (1.38×10^{-23} J/K).Longer τ's indicate low heat absorption due to slower response of molecules to the changing electric field.

Microwave heating has been extensively used from mid 1980s. Microwave interact volumetrically only with the reactants and solvents and for a well designed apparatus, heating can be uniform without causing the decomposition of reactants and products.

Dielectric properties help in predicting electromagnetic field distribution, heating rates, temperature profiles for the reactions and overall understanding of the mechanism of microwave dielectric heating. Dielectric properties play an important role in calculating energy efficiency of the reaction process according to the equation [6]

$P_{abs} = \sigma E^2 = 2\pi f \varepsilon_o\varepsilon'' E^2$

Where P_{abs} is power absorbed (W/m^3), σ is the conductivity (Siemens/m) f is frequency (Hz) ε_0 is the dielectric constant of vacuum and E is the electric field intensity (V/m).

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