Microwave Field Distribution in Multi Layer Structures: A Bio-Engineering Molecular Model

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Abstract - **The overall article objective was to develop an original Bio-Engineering Reverse & Dynamic Molecular Model (BERD MM) for intrinsic control and prediction toward optimization of thermo-dielectrically behavior in Multi Layers Structures (MLS) for energetically performances and safety microwave processing.**

The dynamic correlation MLS behavior/function evaluated with bio-markers/techno-markers and the specific procedures/ parameters prediction for a tailored-end response or a tailored-end product in microwave processing was the strategic research goal.

The MLS dynamic behavior prediction conducted with bio-markers and the parameter/procedures selection in bio-engineering controlled microwave processing was the core of optimized BERDMM for energetically performances and safety industrial procedures.

The process optimization was proposed to be conducted in enhanced field-induced absorption/distribution conditions using in situ controlled heating with Curie- antenna layers.

The predictive optimization model was proposed to be realized with inverse analysis method. The Hazard Analysis (HA) was proposed to be conducted with key-microbiological markers and the Exergetic Analysis (ExA) with key-energetically bio-susceptors.

Keywords - **Microwave, Bio-engineering molecular model, Multilayer structures, Hazard Analysis, Exergetic Analysis.**

I. INTRODUCTION

The general mechanism of microwave heating is energy dissipation in lossy media commonly called dielectric heating. The point of maximum polarization (maximum energetically performance) in complex structures is difficult to attend because of simultaneous effect of mobility, thermal agitation, Brownian movement and collisions [1].

The geometry and dielectric properties of food and biological structures are relevant in the design of microwave industrial procedures & equipment as well as in predicting the specific heating rates and describing the thermal behavior [2, 3].

In microwave heating, the electromagnetic field energy is transformed in thermal energy through direct molecular and selective interaction [4].

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The temperature distribution is primarily determined by the penetration depth of the microwaves into the bio-structure [5, 6] and the rate of heating will be expressed with the Power law equation. Reverse engineering is common used for the developing of competing products and complex & expensive processes [7-9].

The most common approach in inverse thermal transfer protocol involve the surface heat flux assessing using temperature data collected versus time at various known locations inside food with known thermal properties [10]. The article objective was to describe an original BERD MM for energetically performances and safety assurance of microwave processing in multi layers foods and biological structures.

The MLS response assesses by the specific thermo-rheological impact due to unique microwave/materials interactions correlated with equipment design and dielectric properties measurement were the core of proposed reverse bioengineering management for energetically performances and safety microwave processing.

II. RESEARCH METHODOLOGY AND APPROACH

The molecular engineering assessment were proposed to be conducted at low temperatures in order to perfectly monitories the molecular reaction with mass spectroscopy. In order to control the incident energy were proposed the indirect reflectivity method.

The total and critical absorption to resonance will be spectroscopically investigated under viscosity control. The temperature profile was proposed to be evaluated with Maxwell model using the thermodynamic principles. The dynamicity of the heat and mass transfer in the transient stages induce the evolution of the thermal strain-stress gradients, simulated with finite element analysis.

The non-uniform temperature profile of an adiabatic power-law complex material flow is obtained by an analytical method described by thermal energy balance equation. The energy balance equation and the electric field equations with the appropriate boundary conditions are solved using Galerkin finite element method FEM [11]. The relative absorption cross-section of structures reflects the potential effect on microwave field on the biological structures and will be the key-indicator in the HA investigation. The cumulative effect in multiple microwave sequences of exposure will be investigated in MLS and the critical dose expressed in power density (Watt.cm^{-2}) and minimal time to DNA damage will be determined. In vivo, the tests were proposed to be conducted until an acute response at reference the temperature.

The HA were proposed to be treated in the correlation with the frequency and penetration depth in MLS. The reflective reinforcement and dimensional resonance factors will be taking into account.

The process performance and management of critical points developed by HA will be used to determine the microwave processing safety level. In ExA for energetically performance optimization the dynamic specific heat of an isotropic and dielectric MLS were proposed to be investigated with the oscillatory calorimetric protocol.

The inverse analysis was proposed as optimization algorithm to determine an ellipsoid set of solutions around the optimum value.

III. Results and Discussions

A. BERDMM Concept & Design

A.1 Direct molecular mechanism of selective heating. antenna model of susceptors distribution and in situ controlled heating potential

The thermal response depends upon the supply of microwave energy received at the molecular level [12, 13]. In the present proposed model, the intrinsic control of temperature with antenna-markers (bio-molecules or Curie structures/layers) insures the adequate energy flow in molecular level depending on thermo-dielectrically behavior of the lossy structure and the dynamic thermo-rheological response of the non-susceptors particles.

The dipoles and ionic compounds from MLS are considered as direct & preferential microwave partners or antenna-type receptors trough the mechanism of dipolar rotation and ionic conduction.

The antenna model of bio-susceptors distribution due to a dielectrically chart of lossy compounds distribution and predict the kinetic energy/ exergy chart distribution in the screened MLS. In situ controlled heating with antenna Curie-layers were proposed to be investigated for the energetically performance enhancement (uniformity & dynamicity) in safety microwave processing.

A.2 Correlation between the electric power distribution of microwave field inside a cavity and thermo-dielectrically stress gradients distribution in mls microwave processing

In this moment, the prediction of thermo-dielectric behavior for an inhomogeneous structure at different frequencies, temperatures, or various levels of water binding is still an unsolved issue in the microwave processing.

The microwave heating is a nonlinear phenomenon and the present study proposes a modeling protocol in terms of linear non-equilibrium thermodynamics. The temperature distribution is primarily determined by the penetration depth of the microwaves into the bio-structure [14] and the rate of heating will be expressed with the Power law equation.

The chart distribution and free water & polarizable molecules (D-glucose, Tryptophan, tartaric acid) and bio-metal-organic (e.g. methyl-cobalt-amine), as dominant bio-susceptors, were considered to modeling the thermo-dielectric behavior in the microwave processing in the present study.

The dipole, polarizable and bio-metal-organic compounds profile & distribution on the bio-structure dielectric loss and complex dielectric constant will be investigated correlated with the thermo-dielectrically stress gradients distribution in MLS microwave processing.

The stress distribution governed by the pressure distribution in the transient stages of MLS will be described with the Laplacian pressure gradient for the deformed part of the interface.

A.3 Correlation between the dielectric properties (complex dielectric constant), rheological parameters, polarization ability/resonance equilibrium and dynamic specific heat in MLS microwave processing

The microwave processing is greatly influenced by the complex dielectric constant and the differences in heating rate between the layers [14]. In the present BERD MM, the complex dielectrically constant permits a clear prediction of the thermo-dielectrically behavior only for the lossy compounds from the MLS.

The polarization ability/resonance equilibrium defines the factor of thermal efficiently for the bio-susceptors compounds. The local region which highly microwaves absorption generates temperature gradients and thermal stratification.

In the present study the temperature differences over the critical value of temperature gradient were eliminated by heat conduction which equalize the over temperature differences.

B. Thermo-Dielectrically Screening of MLS. Chart of Bio-Susceptors Profile & Distribution

The thermo-physical properties (thermal conductivity, thermal diffusivity, and specific heat) of the bio-susceptors chart, the in situ repartition, dielectrically status of bio-susceptors, the microwave incident energy and penetration are the fundamental parameters in the BERD MM construction.

The loss tangent or dissipation factor ($\varepsilon''/\varepsilon'$), a relevant dielectric parameter, was proposed as key-indicator of the material's ability to convert in heat the absorbed microwave energy. In transient stages, the relationships between ε' and ε'' in transient stages depending on the processing frequency were proposed to be established.

In MLS, the determination of the electric field distribution inside the sample could describe the temperature profile and specific heating rate developed during exposure to microwave field.

The non-uniform temperature distribution in microwave field produces a polarization which reaches its equilibrium value depending on total system dipolar relaxation time. After the active interaction with microwave energy, the susceptors discharge irreversibly and heat conduction and polarization relaxation occurs. The polarization under the pressure of electronic field is instantaneously and the present study considers as entropy sources both the thermal conduction and the polarization relaxation.

C. Bio-markers Thermo-Dielectrically Kinetic Investigation Correlated with Tailored Function Techno-Markers

The BERD MM proposes, as bio-markers kit, tree representative bio-molecules: free water, D-glucose and methyl-cobalt-amine. The BERD MM proposes 3 techno-markers as key-parameters for intrinsic control & prediction toward optimization in MLS microwave processing: the complex dielectric constant, the complex viscosity index and the dynamic specific heat.

The thermo-rheological impact were proposed to be monitored & controlled with the complex viscosity index, storage modulus considered as the real part and loss modulus as imaginary part of the key-rheological parameter.

The complex viscosity index, the critical stress and relaxation time will be investigated in a various range of frequencies and temperature (frequency and temperature sweep tests), in isothermal condition.

The research key is the overall analysis of bio-markers thermo-dielectrically kinetic dynamicity correlated with function tailored techno-markers. In function of thermal energy discharged by the antenna bio-markers, the kinetic changes depending on time-temperature history and key techno-markers were proposed to be investigated.

The yield of bio-marker during heating process was proposed to be determined with Eq. (1) [15]:

$$C(t) = C_\infty - (C_\infty - C_0) exp\left\{ -\int_0^t \left[k_0 \, exp\left(-\frac{E_a}{R}\left[\frac{1}{T(t)} - \frac{1}{T(0)} \right] \right) \right] dt \right\} \qquad (1)$$

where $C(t)$ is marker yield at any time, C_∞ is marker yield at saturation, E_a is energy of activation, R is molar gas constant, $T(t)$ is recorded temperature–time history at the measured point, T_0 is reference temperature.

D. BERD MM in Bio-Molecular Controlled Microwave Processing of MLS

In our reverse engineering model, the dynamic correlation structure-function and the specific procedures/parameters deduction for a tailored-end response, intrinsic controlled behaviour or tailored-made end-product were the strategic research goal.

The present study proposes a new approach in modelling and optimization the transfer coefficient in MLS transient stages.

The unsteady-state one-dimensional energy balance equation [2] due to microwave heating was considered in Eq. (2)

$$c_p \frac{\partial T}{\partial t} = k \frac{\partial^2}{\partial z^2} + q(z) \qquad (2)$$

where ρ represent the structure density, c_p is the specific heat, T is the temperature at the measured point z at the time t, K is the coefficient of total heat transfer of the MLS structure and q (z) represent the dissipation energy at the measurement point z.

E. Optimal Process Predictive BERD MM in Enhanced Field-Induced Absorption/Distribution Procedure for Bio-Molecular Controlled Microwave Processing of MLS

E.1. Thermo-dielectrically screening and kinetic investigation correlated with tailored function techno-markers

The controlled bio-molecular enhancement of thermal performance in MLS microwave processing will be lead with Curie-bio-susceptors structure/layers formed by biogenic nano-particles with specific Curie point: zinc, magnesium and cobalt ferrihydrite.

The bio-molecular engineering with intrinsic control of temperature is the core aspect in the prediction & optimization of dielectrically response & behavior of MLS in microwave processing.

The correlation of bio-markers thermal yield with cumulative lethality will lead to a reliable model for heating patterns assessment in safety condition of microwave processing. In function of generators type (magnetrons, klistrons, amplitrons), the industrial microwave intensity and heating effects increase exponentially.

The Curie bio-layers permit a perfect intrinsic control of structure temperature history because under the specific Curie point show a high energy loss and a specific strongly absorbance coefficient of microwave energy and rise until the critical temperature (Curie point).

E.2 Optimal BERD MM with exergetic analysis restriction factors

The determination of heat transfer coefficient is still an important unsolved aspect in modeling food units operation in which a multiphase's systems change the initial physical state.

The application of the dimension analysis and the formulation of the criteria equation which describe the transition stages are slightly represented in the scientific literature.

The study consider the dynamic specific heat associated with the thermal evolution of a MLS that undergoes quasi-equilibrium heating, related to the equilibrium fluctuations of entropy.

The exergy optimization models establish the efficiency of exergy transfer and conversion and the exergy loose distribution which permit a thermodynamically optimization of heat transfer performance with an inverse method.

The dynamic specific heat is associated to the thermal evolution of a material that undergoes quasi-equilibrium heating, related to the equilibrium fluctuations of entropy.

E.3 Optimal BERD MM with HA restriction factors

The HA will assess the impact on the molecular and sub-molecular level with the lethality cumulative rate investigation for Clostridium botulinum as microbiological marker.

As initial assumption, we consider in our study that the ionization effect could be ignored and we conduct the effects evaluation correlated with the resonance degree for the Curie bio-susceptors structures.

The controlled packages of microwave energy eliminate the ionization effect due to local excess of energy.

In predicting the membrane dielectrically response to the microwave action, the dielectric capacity of membrane cell were treated specifically in correlation with the electro-metabolic processes and frequency.

F. BERD MM Optimization for Energetically and Safety MLS Microwave Processing Using Inverse Method Analysis

The inverse analysis (Fig. 1) is an incremental method proposed as optimization algorithm to determine an ellipsoid set of solutions around the optimum value. The dimensionless continuity, momentum, and thermal energy equations for the MLS with transient viscosity are used.

To solve the unsteady thermal energy and momentum equations with their corresponding initial and boundary conditions a finite-difference method with a well-determinate number of axial and radial directions was used to be x and r, respectively, i.e., $0 \leqslant i \leqslant x$ and $0 \leqslant j \leqslant r$ [16].

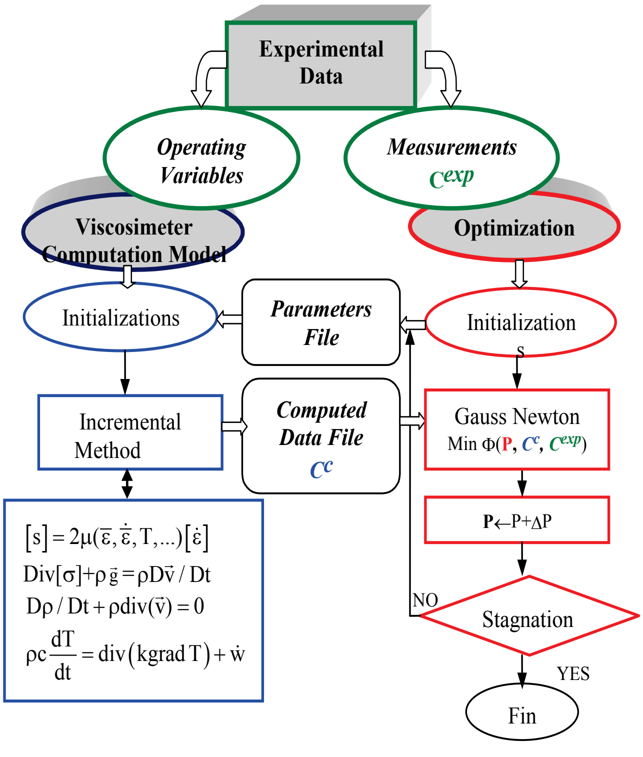

Fig. 1. Inverse analysis algorithm [16]

Consequently, the analytical Fields & Backofen method [17] can be used to identify the rheological parameters by a simple non-linear regression of above estimated experimental shear stress minimizing the cost function Eq. (3):

$$\Phi(P) = \sum_{i=1}^{N\,exp} \left[\tau_i - \tau_i^{exp}(R) \right]^2 / \sum_{i=1}^{N\,exp} \left[\tau_i^{exp}(R) \right]^2 \tag{3}$$

where φ(P) is the cost function, τ is the shear stress and *R* is the perfect gas constant.

In a more general way, using the inverse analysis principle described in the Fig. 1 it is possible to make the parameter identification directly from the measured torques using the objective function Eq. (4)

$$\Phi(K,n,\beta) = \sum_{i=1}^{N\,exp} \left[C_i^c - C_i^{exp} \right]^2 / \sum_{i=1}^{N\,exp} \left[C_i^{exp} \right]^2 \tag{4}$$

where φ(K, n, β) is the objective function and C_i the identified parameters.

The simulation interfacing functions are used to properly update the direct analysis results according to the defined parameters, to determine and associate the analysis results in an optimization algorithm. In the proposed inverse method, an optimized effect was imposed under unknown parameters of influence and the efficiency markers (temperature or velocity) are measured in different locations inside the specific bio-structure [16, 18].

IV. Conclusions

The BERD MM application described in the present article serve for intrinsic control & prediction toward optimization of thermo-dielectrically behavior in Multi Layers Structures (MLS) for energetically performances and safety microwave processing. The thermo-dielectrically behavior prediction with bio-markers for tailored end-functionalities controlled with techno-markers opens the possibility to an accurate intrinsic control of thermal transformation in situ and accurate parameter/procedures selection for a tailored-made end-product.

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