THE DRYING OF FOREST FRUITS IN A MICROWAVE FIELD

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Abstract— In the paper I present theoretical aspects regarding the drying process of forest fruits in a microwave field.

Keywords:* *Electromagnetic field, drying, forest fruits

I. INTRODUCTION

The microwave technologies which have as their basis microwave heating have developed rapidly due to the advantage this heating proceeding offers comparing to the classical proceedings. The effect of the microwaves on the material depends a lot on the physical properties.

Studies concerning the processing of different products were made more recently by Paltin, 1992; S. Lefeuvre, 1993, performed studies on the properties of dielectric materials and the mode they influence the processing in a microwave field. An analysis of the multimode applicators was presented by Metaxas and Meredith, 1994, [1].

They showed the mode of overpositioning of the waves after three octagonal directions, developing successfully a simple technique of measurement of the modes in an empty cavity. This study was then extended by Chow Ting Chan and Reader, 1995, for a loaded cavity. D.C. Dibben, 1996 studied the results of the numerical modelling comparing them with the experimental results for more types of applicators, information which were subsequently used for the developing of complex calculation methods.

H.C. Reader, 1997, developed a method for the determination of distribution of the electric field, which develops between the interior surfaces of the applicator – on the interior metallic surface of the applicator there is a tangential component of magnetic field and a phase different perpendicular component of electric field which develop in space.

In our country there are known different domains of industrial applications of the microwave technique in agriculture: Sterilization, Pasteurization, Devitalization, Seasoning, Drying, Dehydration – Cereal products, pastes, rice, Congelation and temperation – Pastry products, bread, soya beans, flour, amidine, bran.

The advantages it presents determine, nevertheless, new researches which should lead to their application in domains that are as diverse as possible.

The scope we follow is to secure optimum conditions for the processing of forest fruits harvested by the small and medium silvic societies through the realization of a microwave installation which can accomplish the following processes:

- the drying of forest fruits to an optimum moisture content and the active substance for the securing of an adequate storing process;
- the use of unconventional methods of protection (microwave technologies) against the pest insects found in the stored products, taking into account that the chemical control against the pest insects has two great disadvantages: it does not protect the environment and it reduces the quality of the fruits;
- the successful elimination of different bacterial and micotic pathogenic through the treating with microwave of the forest fruits.

II. MODELING OF MICROWAVE HEATING PROCESS

Modeling represents a phenomena using set of mathematical equations. The solutions to these equations are supposed to simulate the natural behavior of the material.

Modeling can be a design tool to develop food that will provide optimum heating results in the microwave oven. In the modeling work, the food system is represented as being made up of many small elements in the simulation process. These discrete elements are joined together to make up the product Lorenson, 1990.

Modeling of microwave drying process can involve two separate parts, one being modeling of heat and mass transfer in the food and another being modeling the electromagnetic field inside the microwave oven cavity for calculating heat generation term Zhang and Datta, 2000, [2]. Modeling of electromagnetic field arises when Maxwell's equations are used for calculating the heat generation term. Maxwell's equations are the basic laws for the microwave propagation Roa, 1994.

Modeling of heat and mass transfer equations uses standard heat transfer equation and the mass transfer terms are included in the boundary conditions of the governing heat transfer equation.

III. GOVERNING EQUATION AND BOUNDARY CONDITIONS FOR HEAT AND MASS TRANSFER

Prediction of temperature profile in the food exposed to microwave is done by solving the following energy balance equation:

$$\nabla \cdot (K \nabla T) + Q = \rho C_p \frac{\partial T}{\partial t} \tag{1}$$

The above governing equation assumes that the heat is transported only by conduction in the forest fruits and the temperature is function of space and time. ρ , Cp and K are density, specific heat and thermal conductivity of the fruits respectively. The heat source term (Q) is function of space and temperature (Saltiel and Datta, 1999; Datta, 2001). The surface of the forest fruits loses temperature to the surroundings by convection and radiative heat loss is not possible in a typical microwave-heating situation since the temperature do not reach high enough to radiate. Evaporative cooling on the surface of forest fruits also influences the temperature profile [3].

Therefore, the boundary condition is (Mallikarjunan *et al.,* 1996):

$$KA\frac{\partial T}{\partial n} = h_t A(T_s - T_0) + \lambda_v \frac{\partial m}{\partial t} \tag{2}$$

where T_s is surface temperature of forest fruits, h_t is the convective heat transfer coefficient, and λ represents the evaporative heat loss λ is latent heat of vaporization and $\frac{\partial m}{\partial t}$ rate of evaporation or moisture transport.

Is calculated from the following governing equation (Datta, 2001):

$$\nabla \cdot (D_m \cdot \nabla \cdot m) = \frac{\partial m}{\partial t} \tag{3}$$

with boundary conditions:

$$n(D_m \mathrm{grad}(M) = \frac{h_m}{\rho}(P_s - P_a) + \frac{S \cdot C_p}{\lambda_v}\left(\frac{\partial T}{\partial t}\right) \tag{4}$$

where, D_m is diffusivity, S is shape factor, λ_v is latent heat of vaporization, h_m is surface mass transfer coefficient, P_a and P_s are partial vapor pressure of air and partial vapor pressure at the product surface, respectively.

Mass transfer of the fruits is temperature dependent and the energy balance equation depends on the mass transfer equations. In addition, fruits properties are temperature dependent.

IV. MAXWELL'S EQUATIONS

The electric fields of microwave are primarily responsible for heating. Nonuniform heating nature of microwave creates temperature gradients and thus causes diffusion, heat transfer, flow, properties change (Ayappa, 1997). These changes can in turn, affect the microwave heating itself. Electromagnetic of microwave, heat and mass transfer in the forest fruits, kinetics of biochemical changes are all involved in the heating process. Therefore, modeling of microwave heating process is highly coupled phenomenon (Ayappa *et al.,* 1992). Forest fruits absorbs the electromagnetic energy and the air in the microwave oven absorb very little of microwave energy. The electromagnetic field inside the microwave oven can be represented by Maxwell's equations (Roa, 1994):

$$\nabla \mathrm{x} \mathbf{E} = -\frac{\partial}{\partial t}(\mu \mathbf{B}) \tag{5}$$

$$\nabla \mathrm{x} \mathbf{B} = -\frac{\partial}{\partial t}(\varepsilon' \varepsilon_0 \mathbf{E}) + \varepsilon'' \varepsilon_0 \omega \mathbf{E} \tag{6}$$

$$\nabla \cdot (\varepsilon \mathbf{E}) = 0 \tag{7}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{8}$$

For forest fruits materials heating is done by electric field primarily through interaction with water and ions. The complex permittivity ε is given by:

$$\varepsilon = \varepsilon' + j\varepsilon'' \tag{9}$$

The Maxwell's equations can predict the electric field E as a function of position and time. Microwave heat generation term (Q) in the heat transfer equation is calculated using this electric field E by (Datta, 2001; Zhang and Datta, 2000):

$$Q = \frac{1}{2}\omega \varepsilon_0 \varepsilon'' \mathbf{E}^2 \tag{10}$$

Using Maxwell's equations and appropriate boundary conditions (discussed in the next section), electric field distribution inside a forest fruits can be calculated. Then the heat generation term (Q) is calculated from the electric field by equation (10). Since the Q varies with respect to position, non-uniform increase in the temperature is observed. This changes the dielectric properties and consecutively the electric field distribution.

The governing equation for electric field is:

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0 \tag{11}$$

The wave number k = α+jβ where:

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon'\left(\sqrt{1+\tan^2\delta}+1\right)'}{2}} \tag{12}$$

$$\beta = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon''\left(\sqrt{1+\tan^2\delta}-1\right)'}{2}} \tag{13}$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{14}$$

Boundary Conditions for Maxwell's Equations

The behavior of microwave can be altered when it encounters boundary or interface. For example, the metallic walls in a microwave oven can impose a boundary condition on Maxwell's equation. As the metallic walls are good conductors and reflect the microwave, electric field parallel to wall is zero. In addition, forest fruits-air interface in the microwave oven and packaging material-fruits can impose boundary conditions (Jia and Jolly, 1992). For example, the change in the microwave propagation at the fruits-air interface because of change in dielectric properties causes changes in the reflected (by the Fruits surface) and transmitted waves through the fruits.

Boundary Condition on Walls

Since the walls of a typical microwave oven are metallic conductor, electric filed parallel to wall (or tangential) and hence the magnetic filed normal to wall disappears (Jia and Jolly, 1992; Ayappa, 1997; Datta, 2001).

$$\mathbf{B}\mathrm{x}n = 0 \tag{15}$$

This natural boundary condition:

$$\mathbf{E}\,\mathrm{xn} = (\nabla \mathrm{x}\mathbf{B})\mathrm{xn} = 0 \quad (16)$$

$\mathbf{E}_{t,air} = 0$ t – tangential direction

$\mathbf{B}_{n,air} = 0$ n – normal direction

Boundary condition on waveguide and ports:

In the waveguide and ports is applied Dirichlet boundary condition (Jolly, 1992):

$$\mathbf{B}\mathrm{xn} = V_m \quad (17)$$

V_m – vector function described by the magnetic field distribution on the waveguide and ports.

Boundary Condition on air-fruits Interface

Suppose the permittivity and permeability of fruits and air are ε_1, μ_1 and ε_2, μ_2 respectively, then the following condition has to be satisfied:

$$\mathrm{nx}(\mathbf{E}_2 - \mathbf{E}_1) = 0 \quad (18)$$

$$\mathrm{n}\cdot(\varepsilon_2\mathbf{E}_2 - \varepsilon_1\mathbf{E}_1) = 0 \quad (19)$$

$$\mathrm{nx}(\mathbf{B}_2 - \mathbf{B}_1) = \mathrm{P} \quad (20)$$

$$\mathrm{n}\cdot(\mu_2\mathbf{B}_2 - \mu_1\mathbf{B}_1) = 0 \quad (21)$$

where n is unit outward normal originating from fruits domain.

This set of equations implies that the magnetic field is chosen for computing the power distribution. This is valid when $\mu_1=\mu_2=\mu_0$ and P=0, i.e., the magnetic field is continuous across the interface and the electric field is discontinuous across the interface. In addition, tangential components of electric and magnetic field are continuous across the interface (Jia and Jolly, 1992; Ayappa, 1997).

However, Datta (2001) argues that the interior of the cavity is to be treated as a dielectric with appropriate dielectric properties of air and fruits. The fruits -air interface does not have to be taken into account in modeling the entire cavity. In that case, boundary condition at the fruits forest-air interface disappears.

V. NUMERICAL RESULTS

The solving of the electromagnetic field problem was made with the help of the Ansoft HFSS 10 programme. From the results of this programme we take over the effective values of the intensity of the electric field corresponding to the network of finite differences used in the problem of the thermal field.

In fig. 1 we present the geometry and the mode of placing the forest fruits in the interior of the applicator.

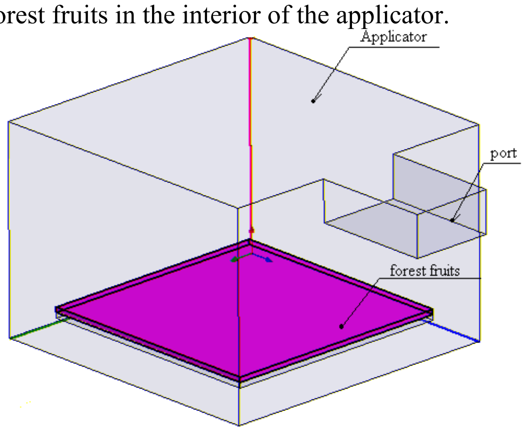

Fig.1. The geometry of the applicator

The drying of the bilberries can be made at about 60 ^{0}C. The process is considered to be finished when the fruits have the soft consistency of raisins.

In fig.2 we present the distribution of the electromagnetic field in complex measurements on the inner faces of the applicator and in the port.

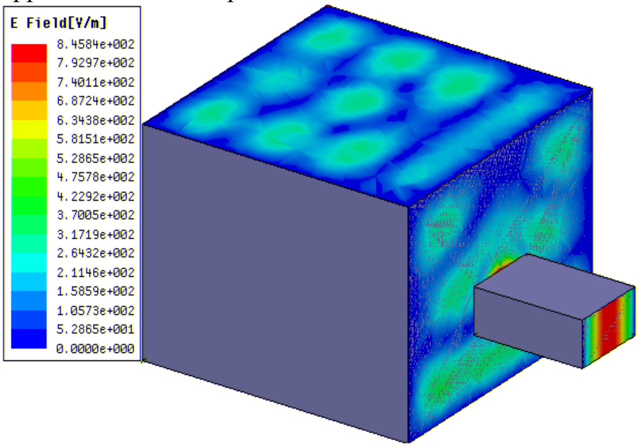

Fig.2 The distribution of the electromagnetic field in complex measurements on the inner faces of the applicator and in the port.

In fig. 3 we present the distribution of the electromagnetic field in the fruit mass.

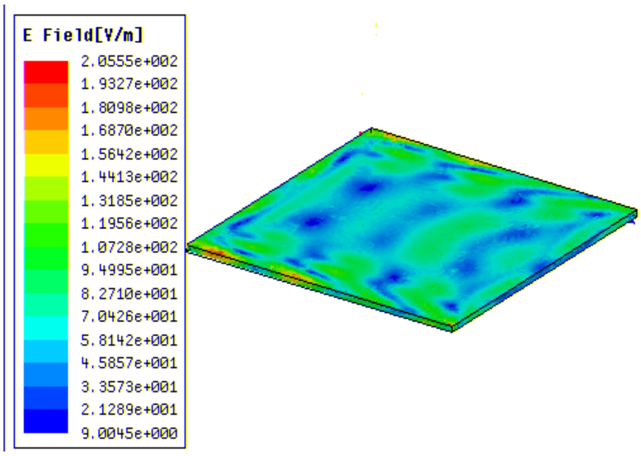

Fig.3. The distribution of the electromagnetic field in the fruit mass

In fig. 4. we present the distribution of the electromagnetic field in the fruit mass, when this contains more layers.

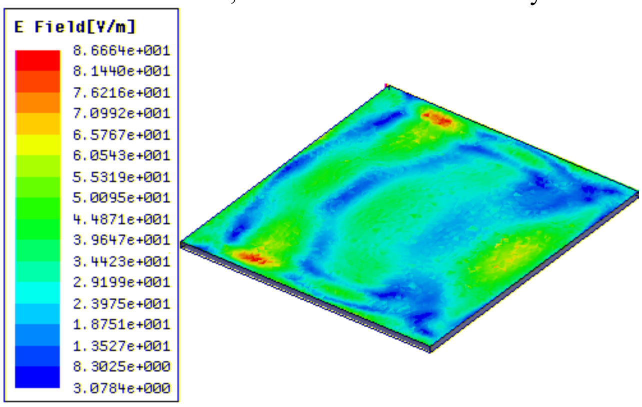

Fig.4. The distribution of the electromagnetic field in the fruit layers

After the drying, the fruits are left for 2-3 days, after which they are assembled. From 7-8 kg of fresh fruits results 1 kg of dried fruits. The final content of moisture is recommended to be between 14-16 %. For the drying of the bilberry leaves, the recommended maximum temperature cannot exceed 40 ^{0}C [8]. The drying of the fruits is done by eliminating the water from the products up to a moisture of 15-25 %, thus securing the concentration of the sugars and acides. From 100 kg of fruits we obtain in dried state 10 kg [10].

VI. CONCLUSIONS

The articificial drying is made through the evaporation of a part of the water found in fresh products with the help of heat in drying rooms thus built that, through drying, the nutritive value, the favour, the taste and the alimentary features characteristic of the fruits should not be affected.

To realize an optimum drying process it is important to establish the following measurements:

- the dryihg system (through direct or indirect radiation);
- the air flow;
- the moisture of the air;
- “the drying ratio”.

The air flow is realized through a natural way, due to the difference of temperature from the drying room and the exterior environment. Good results are obtained when we use ventilators (mode agitator) through which the speed of the air is adjusted, which determines a reduction of the duration of drying and an improvement of the quality of the products.

The moisture of the air is determined according to the nature of the products (ex. for the stone fruits it will be of 20-25% and for the others of 50-60 %).

The drying ratio R_u, allows the calculation of the quantity of water which has to be evaporated, of the thermal energy necessary for the evaporation.

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