DRYING OF BOXTHORN FRUITS IN A MICROWAVE ELECTROMAGNETIC FIELD

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Key words: Boxthorn Fruits, Microwaves, Electromagnetic Field, Numerical modelling, Finite Elements Method.

In this paper, we present some aspects regarding boxthorn drying in a microwave field. This study has an applicative character, being useful in determining some parameters concerning the boxthorn drying, with extension possibility for other forest fruits. The results of the numerical modelling contribute to determining the drying time and the optimum drying power, respectively. We solved the coupled electromagnetic field with the thermal and mass field problem.

1. INTRODUCTION

Dried boxthorn represents a valuable product due to its wide range of nourishing substances. For drying process, boxthorn fruits with dense, succulent pulp (the mass of a fruit is 0.7 g/piece) are considered the most useful. Boxthorn (Lycium) fruits are used for therapeutic purposes in: avitaminoses, anaemia, convalescence, etc. As a medicinal plant, it is recommended for sore eyes treatment, for inflammations and for juices, syrups [1].

The necessity for these studies results from the multiple uses of boxthorn fruits, both in the pharmaceutical and food industry. There are boxthorn fruits cultures all over the country, the processing being done by conventional methods.

The numerical analysis of the electromagnetic field inside the oven, in the presence of the boxthorn fruits, is done with Finite Element Method, using the commercial programmes HFSS (High Frequency Structure Simulator) and obtaining notable results.

The volume power density – p assigned by the microwave field to the boxthorn fruits is obtained from the electromagnetic field solution, meaning the sources of the thermal field problem. Therefore, the thermal field problem can be solved using the well-known methods of the Finite Differences and the Finite Elements.

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In the paper, we propose a procedure by which we accept that water evaporation during the drying process takes place only on the surface of the boxthorn fruits. The evaporation speed depends on the temperature on the surface of the boxthorn fruits. As a result, the water evaporation interferes in the determination of the boundary condition in the thermal problem, through the evaporation latent heat.

From technical point of view, the hypothesis is justified by the fact that in the evaporation process we do not want the thermal field to exceed the boiling temperature. The results of this research are useful for the drying processes control in the microwave field, offering the user the possibility to determine very precisely the power of the microwave source and the drying time in order to avoid the degradation of the fruits.

It is useful to mention the advantage of drying in a microwave field: by reducing the water content, it decreases the support for electromagnetic energy transformation into heat, which confers protection against some super-temperatures. The determination of these parameters ensures obtaining quality products, thus avoiding the degradation of the fruits.

The choice of drying procedure, of optimum regime and of construction of the drying installation must be closely connected to the characteristics of the material and the drying technology of the product, based on the scientific theories of the drying technology [2].

2. THE INFLUENCE OF THE MATERIAL CHARACTERISTICS ON THE DRYING PROCESS OF BOXTHORN

One of the main components that characterize boxthorn as a dielectric material is the oil contained in the pulp of the fruits. The pulp of the fruits contains almost 8 % fat oil. Boxthorn in fresh state has 83 % moisture [2].

During the high frequency electromagnetic field heating, boxthorn fruits change their dielectric properties (ε' and $\tan\delta$).

In the presence of the high frequency electromagnetic field, boxthorn heating depends on the dielectric losses, determined by the values of the relative dielectric permeability ε' and the tangent of the dielectric loss angle $\tan\delta$.

The high frequency electromagnetic field and the electrophysical characteristics of boxthorn fruits influence the heating power and the speed. The elaboration of the technological regime for the fruits' drying is possible if we know the electrophysical properties and the dependences of these properties on the electric field, temperature and moisture of the fruits [3, 4].

The dielectric constant (ε') represents the capacity of the material to store electromagnetic energy. The dielectric loss factor (ε'') represents the material capacity to convert electromagnetic energy into thermal energy. The computation relation for permittivity is the following:

$$\underline{\underline{\varepsilon}} = \varepsilon' - j\varepsilon'' \quad (1)$$

The tangent of the loss angle is the relation between the dielectric loss factor and the dielectric constant:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}. \quad (2)$$

3. THE NUMERICAL ANALYSIS OF THE ELECTROMAGNETIC AND THERMAL FIELD IN THE DIELECTRIC

The dissipated power in the heating systems with microwaves is proportional with frequency, with dielectric permittivity and with distribution of the electric field [5]:

$$p = \omega \cdot \varepsilon_0 \cdot \varepsilon' \cdot \tan\delta \cdot E^2, \quad (3)$$

where E is the intensity of the electric field.

Using Maxwell's equations and appropriate boundary conditions, the electric field distribution inside a dielectric is computed. The governing equation for the electric field is:

$$\nabla \times \nabla \times \underline{\mathbf{E}} - \omega^2 \underline{\varepsilon} \underline{\mathbf{E}} = 0, \quad (4)$$

with the boundary condition imposed on the tangential component of $\underline{\mathbf{E}}$, and gauge condition $\nabla \cdot (\underline{\varepsilon}\, \underline{\mathbf{E}}) = 0$, where $\omega = 2\pi f$ is the pulsation, f – the frequency of the magnetron (2.45 GHz).

The computation of equation (4) is done using the Finite Elements Method with order one vector nodal elements.

The metallic walls in a microwave impose a boundary condition on Maxwell's equation. Because metallic walls are good conductors and reflect the microwave, the tangential component of the electric field is zero.

The theoretical models for temperature and moisture distribution during the drying process with microwaves of the dielectric materials, including food products, were studied in detail in [6, 7, 8]. We present mathematical modelling in a microwave field, respectively the temperature and moisture variation in drying processes with microwaves.

General heat transfer equation:

$$-\nabla \cdot (K \nabla T) + c \frac{\partial T}{\partial t} = p, \quad (5)$$

where: T – temperature (degree); c – volumetric heat capacity (J/m^3·degree); K – thermal conductivity (W/m·degree); p – volume power density (W/m^3).

For the boundary condition, we assumed the following relation:

$$k\frac{\partial T}{\partial n}+\alpha(T_s-T_0)+\alpha_e(T_s-T_0)=0\,, \tag{6}$$

where T_s is the fruits' surface temperature (degree) and α is the convective heat transfer coefficient (W/m^2·degree). α_e represents the evaporative heat loss (W/m^2·degree). The first two terms of equation (6) represent the Cauchy boundary condition.

We introduced the coefficient α_e in order to take into account the water evaporation at the surface of the load. It can be interpreted as being the latent heat of vaporisation requested by the water volume that evaporates on the unit surface in the time unit at a 1 degree temperature difference compared to the exterior.

The value of α_e depends on the atmospheric pressure near the load, on the saturation of water vapours and on the speed with which the air washes the surface of the dielectric [9].

The time discretization of equation (5) with boundary condition (6) can be done by using the Crank-Nicholson technique. For space discretization, the Finite Elements Method of the Finite Differences Method is recommended. We chose the last one. The solution of equation (6) allows us to determine the water evaporation speed of water in boxthorn fruits:

$$\frac{\mathrm{d}m}{\mathrm{d}t}=\oint_{\partial\Omega}\frac{\alpha_e}{\lambda}\left(T_s-T_0\right)\mathrm{d}s\,, \tag{7}$$

where: $\partial\Omega$ represents the boundary of the load that occupies the domain Ω; λ represents the vaporization latent heat [J/kg]. Literature offers different recommendations regarding the choice of the time step [10]. In our case, in order to control the moisture time evolution, it was necessary to impose the time step and the restriction not to reach a too high moisture leap. One can also use other recommendations as those in [11] used for electrical circuits analysis.

For numerical discretization, relation (7) helps us to calculate the quantity of water evaporated at each time step.

4. NUMERICAL AND EXPERIMENTAL RESULTS

This paper presents the 3D numerical modelling of an applicator inside which boxthorn fruits are placed. The problem computation is done using the Finite

Elements Method [12, 13]. The electromagnetic problem is solved for the whole domain of the applicator, and inside it there is the load that occupies the volume Ω.

In reality, the fruits mass is not homogeneous; boxthorn fruits do not have the same moisture and the same dielectric properties. For simplification reasons, we considered boxthorn fruits as a homogeneous and uniform mass. Therefore, we obtained average equivalent material parameters, which take into account the percent of boxthorn fruits and air.

We chose an ε for a certain temperature t_0, and we determined the electromagnetic field with the HFSS programme. For simplicity, we determined ε just one time at the beginning of the simulation.

We calculated the losses at different time steps, taking into account the dependency of ε and tanδ on temperature and moisture, but the effective value of *E* remains the one initially calculated.

The dependency of ε and tanδ as a function of moisture is given in Table 1.

Table 1

Moisture [%]	Dielectric constant ε′	Tangent of the loss angle tanδ
15	6,06	0,194
20	6,65	0,055
25	6,26	0,034
30	4,71	0,035

In the HFSS (High Frequency Structure Simulator) software, we used a network consisting of 121.320 tetrahedrons. The software adapts the accuracy of the network by itself for the computation domain.

We solved the thermal problem coupled with the mass problem.

Taking into account the small sizes of boxthorn compared to the sizes of the oven, we admit that in the tray with perforated walls – that allow the evaporation of water – the small tray is placed in the middle of the oven. This is loaded with boxthorn and we have an equivalent homogeneous environment in which the physical parameters are obtained through weighted average between the parameters of the boxthorn fruits and those of the air.

To calculate ε, we used the equation:

$$\varepsilon_{ech} = \frac{\varepsilon_b \cdot V_b + \varepsilon_a \cdot V_a}{V_b + V_a}, \tag{8}$$

where: ε_b, V_b represents the permittivity, respectively the volume of fruits, ε_a, V_a represents the permittivity, respectively the volume of air.

Obviously, this approximation can introduce deviations from the real solution especially regarding the values of thermal conductivity α. Luckily, the value of thermal conductivity does not greatly influence the results in equation (6).

We used the Finite Differences Method to solve the thermal problems.

For the numerical calculation we chose: $\alpha_e = 0.4516$ W/m$^2\cdot$degree; $\alpha = 20$ W/m$^2\cdot$degree; $c = 60$ kJ/m^3 degree, $k = 0.142$ W/m$\cdot$degree, $\lambda = 2260$ kJ/kg.

In Fig. 1, we present the geometry of the microwave applicators. The dimensions of the applicator are 310 mm × 310 mm × 210 mm. The applicator is equipped with a rectangular wave guide, while the working frequency of the applicator is 2,45 GHz, and the power adjustable between 300 and 800 W.

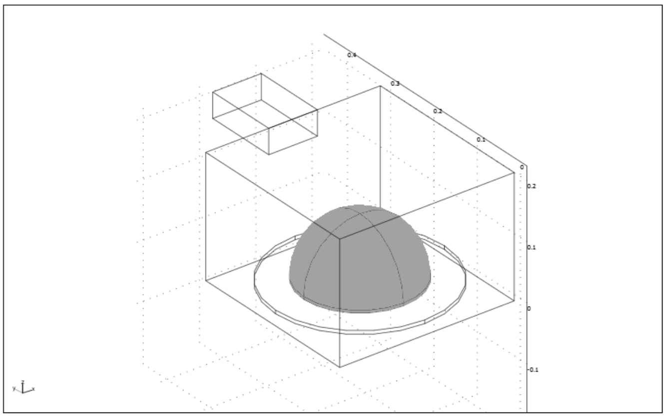

Fig. 1 – Application geometry.

In Figs. 2, 3, we present the distribution of the electric field in a perpendicular plane on the port and in the boxthorn fruits.

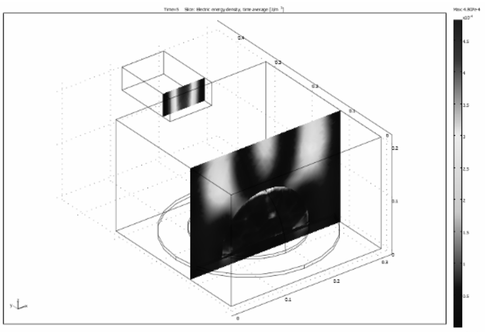

Fig. 2 – Electric field distribution in port.

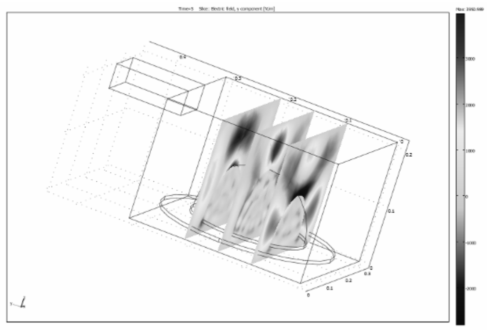

Fig. 3 – Electric field distribution in boxthorn fruits.

In Fig. 4, we present the temperature distribution on the surface of the boxthorn fruits.

In Fig. 5, we present the temperature variation in the boxthorn fruits mass determined through numerical modelling. After modelling, the processing time is 240 s, while the temperature in the fruit mass reaches 80 ^{o}C.

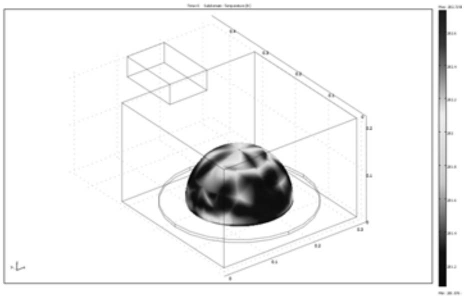

Fig. 4 – Temperature distribution in the boxthorn fruits.

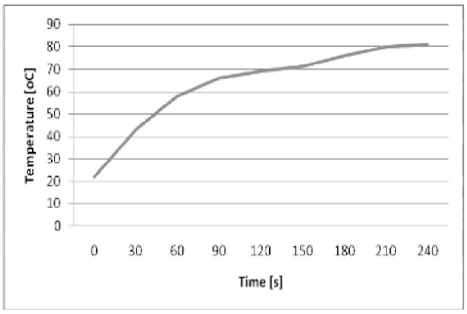

Fig. 5 – Temperature variation (*P* = 300 W).

In Fig. 6 we present the temperature variation in the fruit mass at the applicator power equal to 300 W, respectively 450 W. The characteristic T1 presents the temperature variation corresponding to a power of 300 W. We finally got a temperature of 78 ^{o}C.

The characteristic T2 presents the temperature variation corresponding to a power of 450 W. We finally got a temperature of 82 ^{o}C.

Fig. 7 shows the variation of moisture in the drying process of boxthorn fruits.

From the experimental results, we conclude that if we use a 300 W constant power, the drying time is 240s and fruit moisture reaches 17%. If we use a 450W constant power, we reduced the processing time to 180 seconds to reach the final moisture value of 11%.

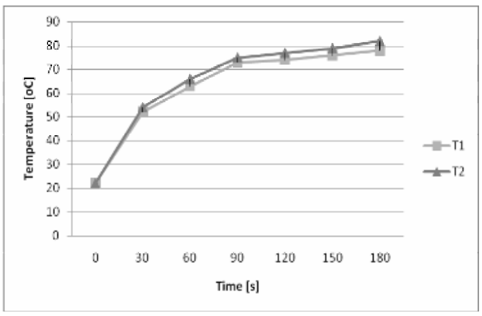

Fig. 6 – Temperature variation (*P* = 300/450 W).

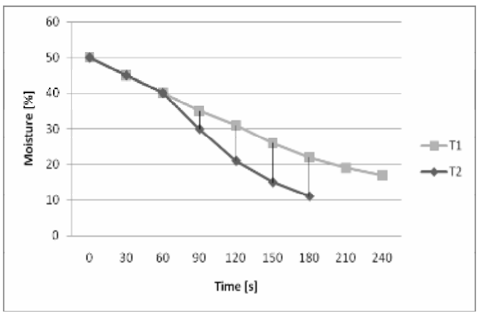

Fig. 7 – Moisture variation (*P* = 300/450 W).

5. CONCLUSIONS

The results obtained from numerical modelling allowed the establishment of initial parameters of the drying process of boxthorn fruits. These parameters are useful for controlling the microwave field drying processes, offering the user the possibility to determine the microwave source power at the initial drying stage and the drying time. In this way, we avoid the degradation of the boxthorn fruits.

Sometimes, during the heating first phase, when the risk of thermal agitation appears, we used a smaller power (300 W), reducing the risk of boxthorn fruits deterioration. The presented method can also take into account the oven feeding at powers that vary in time, amplifying the effective values of the intermittence of the electric field obtained through HFSS; at the beginning of the computation, the amplification depended on time.

Fig. 7 presents an experimental measurement. In the final phase of the drying process, we increased the power to 450 W, thus reducing the drying time from 240 s to 180 s.

Some conclusions referring to the main ideas: the hypothesis of the water evaporation only at the surface of the load is because the temperature inside the boxthorn is limited under the evaporation temperature (100 °C) (not to damage the fruit); the evaporation takes place on the surface of each fruit, but we locate it only at the surface of the entire load.

Future research will concentrate upon a mathematical model elaboration in which the evaporation at the surface of the boxthorn grains is taken into account.

Because of the large number of the boxthorn fruits in the box, the physical parameters mediation for the load occupied by grains and air is a compulsory modelling.

One can also try other mediation relations different from that with volumetric weights. The procedure presented in the paper will be applicable in the future also for moving loads (rotation of the turntable). Therefore, it is necessary to solve first the electromagnetic problem for more positions of the load and maybe to use interpolation procedures.

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