Progress In Electromagnetics Research B, Vol. 41, 419–439, 2012

HIGH FREQUENCY ELECTROMAGNETIC FIELD MODELING AND EXPERIMENTAL VALIDATION OF THE MICROWAVE DRYING OF WHEAT SEEDS

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Abstract—The aim of this study is to determine the effects of the thermal treatment with microwaves on the germination of wheat seeds, type Apache × Renan for different processing parameters. With the experimental data we intend to find out the optimum balance between applied energy and material humidity so that the material can be dried without its structure being adversely affected. From the analyze of experiments regarding wheat seeds drying with the aim of obtaining a quality product we mention that the best results are referring to the situation of using the microwave power of 0.3 W/g combined with hot air stream and having the measured temperature in the seed bed below the value of 75°C.

1. INTRODUCTION

Microwaves are a more efficient method of drying than traditional thermal treatments, because energy is delivered directly to the volume rather than by conduction through the surface [1, 2].

The dielectric properties of materials depend on several factors. When talking about hygroscopic materials such as foods, the amount of water in the material is a dominant factor. The dielectric properties also depend on the frequency of the applied alternating electric field, the temperature of the material and on the density, composition and materials structure. In the case of granular materials the bulk density

Received 9 April 2012, Accepted 4 June 2012, Scheduled 25 June 2012

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of the air particle mixture is a factor that influences the dielectric properties.

The measurement of permittivity and permeability in the microwave frequency range has become an important issue to be studied [3].

The permittivity or dielectric properties of agricultural materials and food products are a key parameter that determines how they interact with an electromagnetic field. Frequency, moisture content, bulk density and temperature are the major factors affecting dielectric properties of agricultural materials and food products [4, 5].

In the present work, with the analyze of simulation results and experimental determinations, it was conducted the optimum solution for drying seeds in the microwave field using the lab installation.

Research regarding microwave drying of agricultural products have been studied since 1963 by Hall, by Fanslow and Saul in 1971 [6]. Recent studies of using microwaves in food production were conducted by Venkatesh and Raghavan in 2004, Vadivambal and Jayas in 2007 [7]. During the drying of grains in the microwave field, the heat is produced instantly throughout the kernel and causes a rapid mass transfer of moisture emerging out. The moisture content of grains is reduced by drying to the appropriate humidity level required for the crops to be stored [8].

The need to reduce field losses, better utilization of resources and time needed to prepare the land for the next crop, are some of the reasons why crops are harvested at higher moisture content [9].

2. FIELDS PROBLEM FORMULA

An important stage in beginning the research is the study of the electromagnetic field inside the microwave applicators.

This implies association of a numerical model to the electromagnetic field problem, model that is precisely described by the Maxwell equations:

$$rot\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{1}$$

$$rot\mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \tag{2}$$

$$\mathbf{D} = \varepsilon \mathbf{E} \tag{3}$$

$$\mathbf{B} = \mu \mathbf{H} \tag{4}$$

$$\mathbf{J} = \sigma \mathbf{E} \tag{5}$$

where: $\mathbf{E}$ — Electric Field Strength; $\mathbf{B}$ — Magnetic Induction; $\mathbf{J}$ — Density of the Source Current; $\mathbf{H}$ — Magnetic Field Strength;

D — Electric Induction; μ — Magnetic Permeability; σ — Electrical Conductivity; ε — Electrical Permittivity.

The homogeneity of the electromagnetic field on the surface of the dielectric is influenced by its position inside the applicator. A non-homogeneous distribution of the field will lead to a non-homogeneous temperature distribution. Consequently, we need to study the thermal field.

Thermal diffusion within the grains as a result of the microwave heating process also needs solution:

$$-div k \mathrm{grad} T + c\frac{\partial T}{\partial t} = p \tag{6}$$

Imposing the boundary condition:

$$-k\frac{\partial T}{\partial t} = \alpha(T - T_0) \tag{7}$$

where: k — thermal conductivity; T — Domain temperature, c — Specific heat; T_0 — exterior domain temperature; α — surface thermal transfer coefficient; p — represents the power medium density that transforms from electromagnetic energy to thermal energy.

Power dissipated per unit volume is the measure introduced in the thermal field equation in order to follow the evolution of the temperature in the dielectric.

For dielectric materials, heating is achieved by the microwave field, primarily through interaction with water and ions. The specific losses are calculated using the relation:

$$P = \frac{\omega\,|\varepsilon|\tan\delta}{2}E^2 \tag{8}$$

where: $\underline{\varepsilon} = \varepsilon' - j\varepsilon''$; $|\varepsilon| = \sqrt{\varepsilon'^2 - \varepsilon''^2}$; P — power density per unit volume; ε' and ε'' represent the real and imaginary part of the complex permittivity, $\tan\delta$ is the loss tangent; ω — is the angular frequency, E — electric field strength.

The most difficult aspect concerning mathematical modeling of the drying processes in microwave field is the fact that the solution of electromagnetic field problems are coupled with thermal problems.

When solving the coupling problem there has to be taken into consideration a few aspects like:

- Permittivity depends non-linear on humidity and temperature of the material and on the work frequency;
- Humidity dependence of the thermal convection coefficient at surface, caloric capacity, thermal conductivity;
- Boundary conditions depend on the evaporation speed of water, water pressure vapors, on latent evaporation heat [10].

3. NUMERICAL SIMULATION

Designing microwave heating equipment for dielectric materials (applicator sizing and the selection of the appropriate microwave generators) is not an easy issue.

Specialized technical literature [11] offers analytical models for their dimensioning, approximations obvious due to neglecting of thermal and electromagnetic field coupling, mass problems and eventual of movement. This approach, if taking into account the dielectric parameters modification during their processing (heating/drying/ biological treatment), becomes a complex and hard to solve problem. For these reasons, sometimes we approach this problem simplified [12].

Thus, in the present case of analysis for treating agricultural seeds in microwave field, after a classic analytic calculation concerning applicator dimensioning and selection of the microwave generator parameters were performed more numerical simulations of the electromagnetic field within the applicator using the facilities offered by the numerical analysis software Ansoft HFSS (High Frequency Structure Simulator) [13, 14].

During the numerical simulation stage by using numerical analysis software was pursued to obtain a uniform distribution of the electromagnetic field in the dielectric's volume by modifying the position of the dielectric in the cavity. From the whole set of modeling and simulations that we conducted during our research, the most suggestive results were chosen.

In the following are the results of the simulation in order to distinguish the electric field distribution in the seed bed placed into the applicator.

It is assumed that the load is in steady state. The supposed dimensions of the applicator are: $x = 109.22\,\mathrm{mm}$, length $y = 300\,\mathrm{mm}$ and height $z = 54.6\,\mathrm{mm}$. Inside the applicator, a sample recipient is produced, which is microwave transparent and consists of a seed bed having dimensions of 103 mm length and 70 mm width. In the inferior part, the sample recipient has holes that permit air forced ventilation from an auxiliary turbine.

The dielectric constant decreases with increasing frequency, but the loss factor may increase or decrease as frequency increases, depending upon the frequency and the moisture content of the wheat [15]. The considered dielectric properties for the wheat seed are ($\varepsilon' = 2.8$ and $\tan\delta = 0.14$) separated from the environmental medium which is considered air, the structure being anisotropic.

During researches, different simulations of the resonant cavity of the laboratory equipment were considered, presented in Fig. 6. The material parameters were modified together with the dimensional and dielectric's position.

Based on this study were computed and visualized the electromagnetic field distribution and also data concerning the reflected power to the magnetron, waveguide, expressed through the S Parameters (dB). The most concluding results of the simulations are presented in Figs. 1–3.

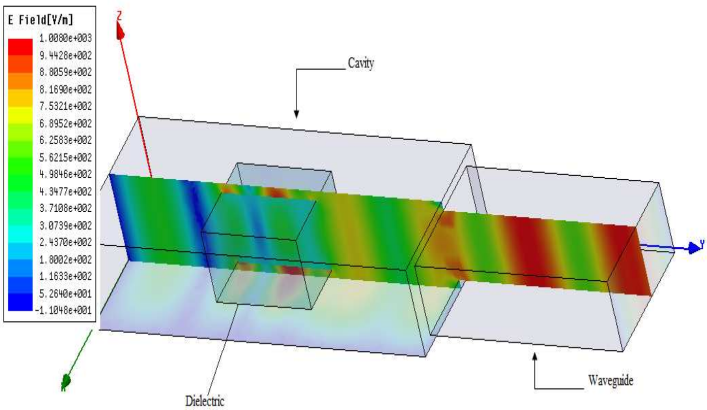

Figure 1. Electric field strength distribution in transversal section through microwave applicator and waveguide.

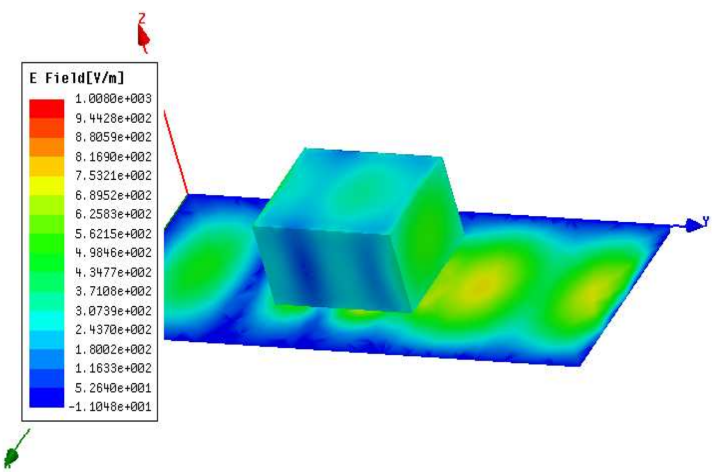

Figure 2. Electric field distribution over the base plan of the cavity and dielectric.

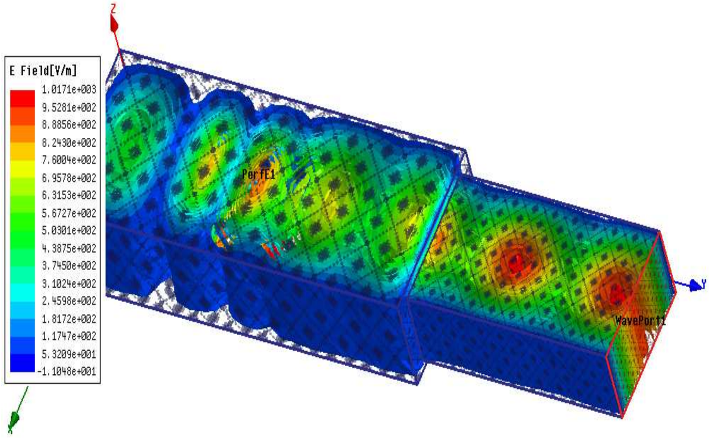

Figure 3. Settings regarding boundaries and wave port. Electric field distribution through the geometry.

Figure 1 presents the geometry of the simulation and shows the electric field distribution in transversal section through the cavity, dielectric and waveguide. Fig. 2 describes the electric field distribution over the base plan of the cavity and dielectric. Fig. 3 shows the settings regarding the boundaries and the wave port's position and also presents the electric field distribution through the entire geometry.

The results obtained according to the position and humidity of the dielectric were not only based on the simple analysis of the electromagnetic field distributions. On the base of these stays an elaborated study of all results obtained by using the numerical modeling software Ansoft HFSS.

The software permits to calculate and visualize data regarding reflected power to the magnetron (waveguide) expressed through the S parameters, in db. Taking into consideration these results and making the rigueur transformations, it is observed that when the reflected power to the waveguide is minim the dielectric absorbs a maximum quantity of possible power (see Figs. 4 and 5).

The two situations presented in Figs. 4 and 5, of the reflected power to the magnetron, were chosen for two different values of the grains humidity: — first one with a higher rate: $U_1 = 23.8\%$ (with the relative permittivity $\varepsilon' = 3.1$ and dielectric loss tangent $\tan\delta = 0.25$) and the second with a low rate of the humidity: $U_2 = 10\%$ (having the relative permittivity $\varepsilon' = 2.8$ and the dielectric loss tangent of $\tan\delta = 0.14$).

Analyzing the electromagnetic field distribution over the dielectric's surface can be observed the maximum and minimum points specific to the propagation mode TE_{10}.

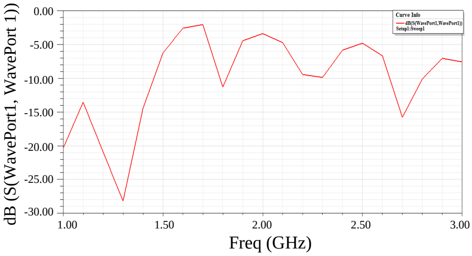

Figure 4. Reflected power to the magnetron expressed through the S parameters, in dB.

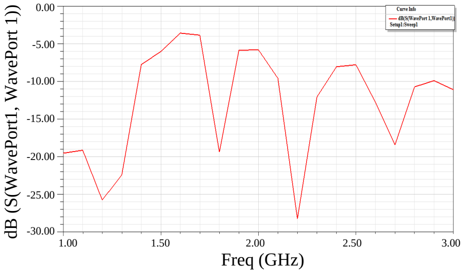

Figure 5. Reflected power to the magnetron expressed through the S parameters, in dB.

Figure 6. Laboratory installation used for microwave/cold/hot air processing of granular dielectric materials.

Taking into consideration the electromagnetic field distribution there can be affirmed that the thermal field will also have a similar distribution, validated through experimental determinations, Fig. 14.

Thus analytical calculations, electromagnetic field simulations, referring to applicator and dielectric, interpretation of obtained results and designing experience in the field of the present work study lead to the realization of a microwave heating equipment (Fig. 6).

4. RESULTS AND DISCUSSIONS

The aim of this study is to determine which drying parameters are best suited for treating wheat seeds. The drying parameters that are important when processing seeds using high frequency field are: the absorbed power, the humidity, the temperature and the dielectric properties of the material. The second step of the study, once the drying process is completed, is to analyze the germination for the studied samples and compare it with the germination rate of the witness sample. Often, in the agricultural industry conventional driers with a hot air stream are used to good effect. The idea of combining these conventional driers with the power of the microwaves contributes to the improvement of the drying process [16].

In literature are often found studies that utilize rewetted cereals, instead of fresh material. This seems to be common practice when freshly harvested grains are not available for the desired study [17]. In our experimental data, we used the stand within the laboratory of Microwave Technologies, Electrical Engineering Department, Faculty of Electrical Engineering and Information Technology, University of Oradea [18] (See Fig. 6).

The experimental installation comprises the following: Microwave generator with it maximum power of 850 W, waveguide WR340, single mode applicator, dummy load, hot air source with temperature regulator, electrical inter-blockage, stub tuner with 3 adjusters, directional coupler. The equipment is supplied at $220\,\mathrm{V} \pm 5\%$ voltage and 50 Hz frequency.

The microwave generator is provided with adjustable power and an included potentiometer in order to adjust the microwave power. The single mode applicator has a parallelepiped shape with inner sizes of $109.22 \times 54.6 \times 300\,\mathrm{mm}$.

The single mode applicator is designed so as a hot air stream may enter from below and flow upwards through the seed bed in order to eliminate the moisture from the outer surface of the seeds. This is done in order to avoid hot spots that may occur in the seed bed and so to ensure a homogenous temperature throughout the entire mass of the seeds.

The dummy load placed at the end of the installation will eliminate the residual high frequency electromagnetic field energy. If the dielectric material cannot absorb efficiently the microwave energy, a significant quantity of energy may be reflected towards the microwave generator. The excessive quantity of reflected energy may deteriorate the microwave generator. In this sense the circulator protects the equipments of the system by determining the displacement of the microwaves in a single direction. Inside the circulator are designed three ports: the first one is connected to the microwave generator, the second one is connected to the applicator and the last to the dummy load.

Parameter variation during the seed drying process was observed by continuously measuring the microwave power, of the absorbed power, of the exit airstream humidity, of the hot air temperature that is set up not to exceed 55°C, of the temperature measured on the seed bed and also by adjusting the plunger position.

The temperature in the seed bed has been measured by the use of a thermometer with optical fiber of type "Pico Power Sens 6", by sticking the seed bed. The humidity and temperature of the exit air have been measured by the hygrometer Lutron YK-90HT.

The samples have been obtained on wheat seeds, humidified previously, type Apache × Renan. The target during research was to determine what temperature, power and humidity conditions are favorable to germination and quality of the seeds treated by microwaves.

For each conducted experiment, from 30 to 30 seconds, the following was measured: the direct (absorbed) and reflected power, the temperature and humidity of the exit airstream exiting the applicator and the temperature in the seed bed. Based on Equation (9), humidity was extracted out of the seed bed.

In order to correctly measure the germination and quality of the seeds, the samples were taken to the Seed Center in Oradea with the aim of analyzing the alterations that take place in the grain with respect to proteins, gluten and the zeleny value and finally, the germination and quality of samples were compared to the witness sample.

The humidification procedure for the wheat grains was comprised of the following steps:

- for the beginning, the humidifying of a quantity of 700 g of wheat with the initial humidity of 16%;
- the humidification procedure consisted of placing the 700 g wheat grains into a glass container. The container was filled with water just over the wheat grains. The initial temperature was 25.6°C;
- the grains were left in the water for 2 hours, then wringed on a humid towel for 2 hours and then left in the fridge for 12 hours;
- of the 700 g of humidified seeds, samples of 100 g each (m_i) were processed, with a final humidity of 26.6%.

The initial and final humidity was measured with the grain humid meter Multi Grain RO 089/97. In order to correctly measure the final humidity, at the end of the treatment process, the wheat grains were left to cool off and then placed in the humid meter.

Before every experiment, the balance has been set to indicate a mass of 0.0 g, with the container placed on the platform. The measurements were carried from 30 to 30 seconds without interrupting the functioning of the unit.

In order to determine the humidity percent of dried seeds, we used the initial mass, before drying m_i and the final one, after the drying m_u (STAS 10349/1-87):

$$U[\text{Humidity}] = \frac{m_i - m_u}{m_u} \times 100[\%] \tag{9}$$

The outcome of the microwave power has been studied on 6 samples:

1. Using the even power of microwaved of 0.3 W/g/10 minutes for drying 100 g of seeds previously humidified:

a. without airstream;

b. with airstream at the temperature of the environment (cold air stream);

c. with hot air stream.

2. Using the even power of microwaves of 0.4 W/g/10 minutes for drying 100 g of seeds previously humidified:

d. without airstream;

e. with airstream at the temperature of the environment (cold air stream);

f. with hot air stream.

While drying seeds in microwave field, the first detail that draws our attention is the change in grain color, fact also reported by Warchalewski et al. in 1998 [19]. While raising the temperature in the seed bed to over 60–70°C, the grains turned glassy.

For the samples dried only in microwave field, without airstream, a film of water was noticed at the end of the treatment over the dielectric material due to the lack of ventilation in the seed bed — which also led to a lower humidity level.

For sample 1a, the humidity value calculated in the Equation (9) was $U = 5.26\%$ and for sample 2a (where the processing power was increased to 0.4 W/g) the value $U = 7.52\%$. We noticed that by increasing the power, a higher quantity of water was driven out of the dielectric.

As with airstream at environment temperature, in the case of samples 1b and 2b, the same value of humidity was noticed $U =$

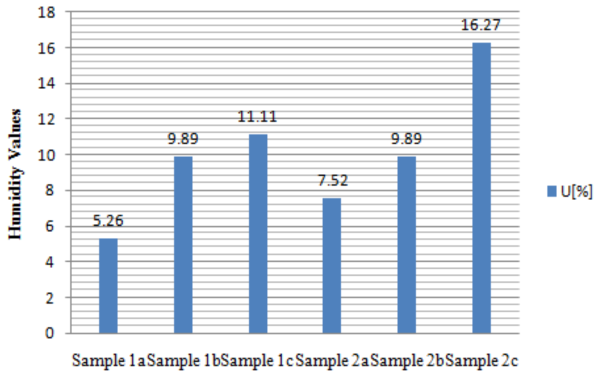

Figure 7. Humidity eliminated from the seed bed.

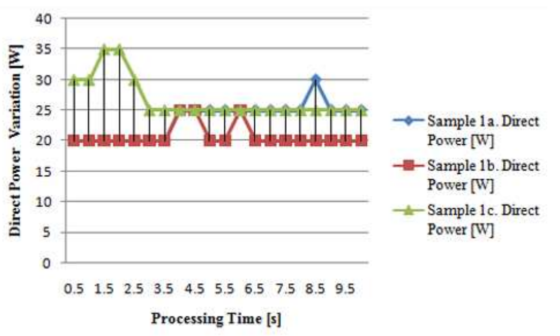

Figure 8. Direct power variation in constant heating using 0.3 W/g.

9.89%, even though the power applied was higher for sample 2b. For samples 1c and 2c, where hot airstream was applied in the seed bed, the values obtained were: $U = 11.11\%$ and $U = 16.27\%$ (see Fig. 7).

During experiments 1a and 2a (where only microwave power was used), the increase of the exit air humidity was observed — from 38.8% to 94.8% (see Fig. 10), respectively from 36.7% to 94.6% (see Fig. 13) which proves the water film forming at the surface of the dielectric.

During treatment using only microwave power, applying airstream is recommended for avoiding temperature variation and consequently hot points forming in the seed bed. Hot points may influence the grain quality. The highest temperature variation reached 120.9°C and 177°C (see Figs. 9 and 12) were recorded for samples 1a and 2a where no airstream was present. On the same time, these 2 samples have displayed important variations of absorbed power, as can be seen in Figs. 8 and 11.

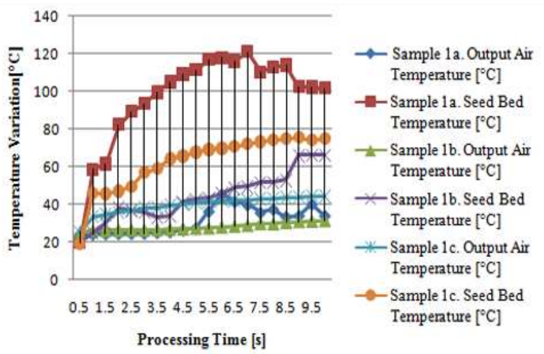

Figure 9. Temperature variation in constant heating using 0.3 W/g.

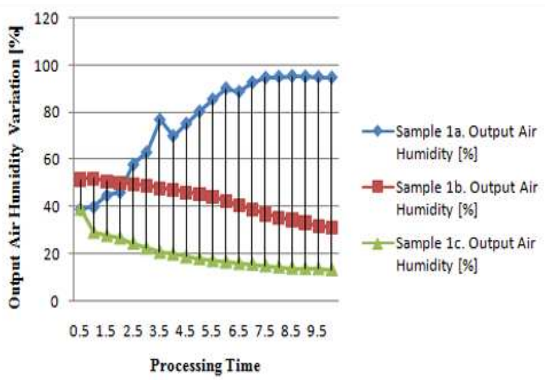

Figure 10. Output air humidity variation in constant heating using 0.3 W/g.

When using microwave power with cold airstream, in the case of samples 1b and 2b, the exit air humidity dropped from 51.5% to 31.2%, and from 42% to 25% respectively (see Figs. 10 and 13).

The direct power, or, more accurately, the absorbed power in the dielectric, displayed the highest values for sample 1c, where although the generated power was 0.3 W/g, the seeds absorbed up to 0.35 W/g in the second minute of testing, point after which it remained constant to 0.25% (see Fig. 8).

Together with power absorption, the decrease of exit humidity was noticed — from 39% to 13.1% (see Fig. 10). Even though an increase in power absorption was induced, the temperature in the seed bed did not cross over the value of 75.5°C (see Fig. 9).

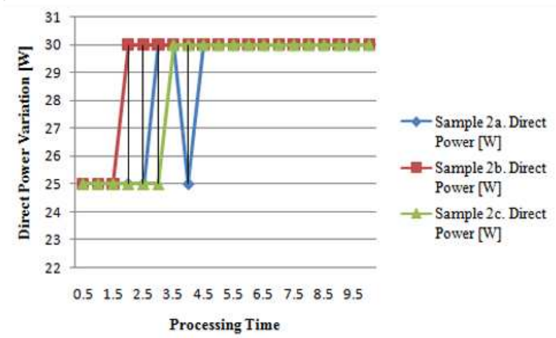

Figure 11. Direct power variation in constant heating using 0.4 W/g.

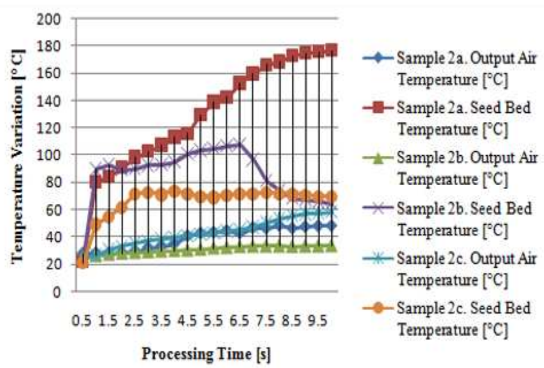

Figure 12. Temperature variation in constant heating using 0.4 W/g.

Another sample that displayed a decrease in the exit air humidity was sample 2c, where, as in the case of 1c, we used hot airstream and we increased the generated power to 0.4 W/g. This decrease was recorded from the value of 75.4% to 11.9% (see Fig. 13), the absorbed power by the dielectric was of 0.25–0.3 W/g. The temperature measured in the dielectric did not rise over 73.6°C (see Fig. 12).

The air temperature measured at the exit from the dielectric did not display variations or higher values for any of the samples, the highest temperature experienced in the case of sample 2c, of 58.2°C (see Fig. 12).

A less expected and less explainable situation — that will present an important factor in our future studies — represents sample 2b, where, although we used airstream at environment temperature, the temperature measured in the seed bed displayed high variations; at

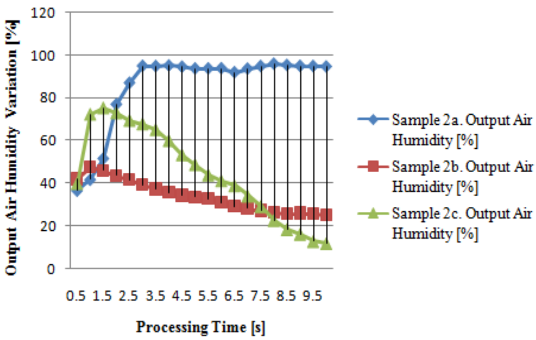

Figure 13. Output air humidity variation in constant heating using 0.4 W/g.

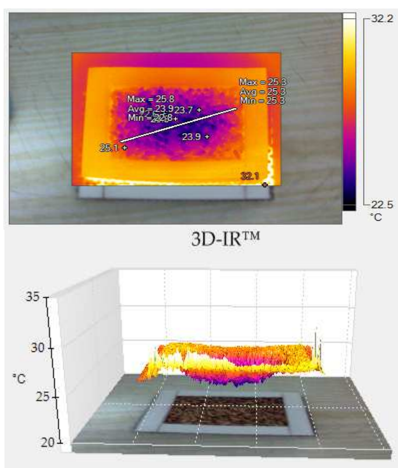

Figure 14. Temperature distribution over the seed bed and the 3D distribution of the temperature of the witness sample.

minute 6 it reached a value of 107.7°C, only to settle afterwards until the end of the drying process to 64.3°C (see Fig. 12).

Measuring the final humidity of the seed grain is important for storing seeds in optimal conditions. According to specialty literature, the humidity for the optimal storage of seeds is near the value of 14% [20].

The final humidity for the samples dried in microwave field is: for sample 1a — $U_{\text{fin}} = 20\%$, for sample 1b — $U_{\text{fin}} = 17.2\%$, for sample 1c — $U_{\text{fin}} = 14.5\%$, for sample 2a — $U_{\text{fin}} = 18.9\%$, for sample 2b —

$U_{\text{fin}} = 16.4\%$ and for sample 2c — $U_{\text{fin}} = 13.3\%$. After showing these results, we can state that the samples that comply with the storing requests are 1c and 2c, samples that experienced the highest value of humidity removed from the seed bed.

The success of this experiment consisted of the value of the germination rate and of the quality of the microwave treated seeds. In the case of using only the microwave power, without airstream, we had contradicting results: for sample 1a the germination value was $G = 35\%$ (65% of the grains being dead) and for sample 2a — $G = 98\%$. This result can be explained by the fact that the temperature in the seed bed raised for sample 2a to the value of 177°C, which determined cracking the grain and thus favoring germination.

In the case of using microwave power with airstream at environment temperature, samples 1b and 2b displayed the following results: $G - 80\%$ and $G = 92\%$ respectively.

Using the hot airstream with microwave power of 0.3 W/g and 0.4 W/g favored not only removing the excess water from the dielectric, but also the germination rate, $G = 96\%$ experienced for both samples.

For the witness sample, a germination of $G = 95\%$ was experienced.

The experiments that have displayed a better germination rate

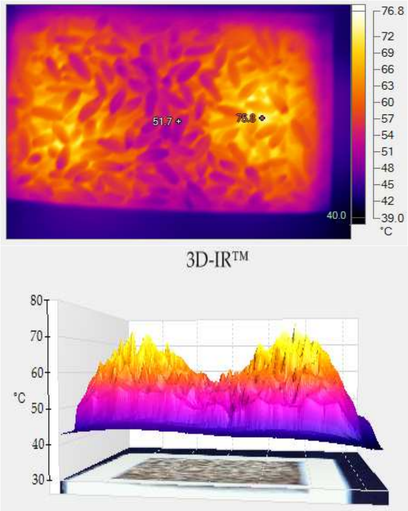

Figure 15. Temperature distribution over the seed bed at the end of the process using the power of the microwaves with hot air stream and the 3D distribution of the temperature.

than the witness sample were the ones for which hot airstream was used with 0.3 and 0.4 W/g and sample 2a.

Germination was determined with germinators of type Linhard, sterilized; filter paper was used, soaked with tap water, kept under the niche at 20 ± 2–$3°C$. The germination is considered finished when the root has a length equal to the length of the grain, and the trunk has 1/2 of this length [20, 21].

In order to compare the numerical modeling part with the experimental one, at the end of each drying process thermal images were taken with the thermal camera Fluke F32i.

We chose to present the thermal sample power for which we obtained the best values for the germination ratio: 1c, 2c and 2a, as well as for the witness sample.

In Fig. 14, we present distribution of the thermal field in the seed bed and the 3D distribution of the temperature for the witness sample.

Figure 15 displays distribution of the thermal filed on the surface of seeds and of the 3D distribution of temperature at the end of the drying period for sample 1c.

Figure 16 displays distribution of the thermal field over the surface of seeds and the 3D distribution of the temperature at the end of the

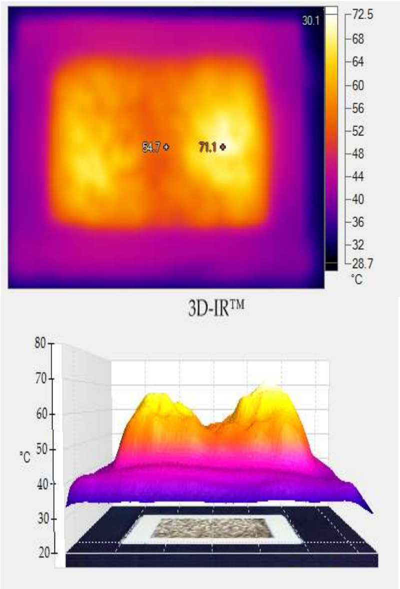

Figure 16. Temperature distribution over the seed bed at the end of the process using the power of the microwaves with hot air stream and the 3D distribution of the temperature.

drying period for sample 2c.

Figure 17 displays distribution of the thermal field over the surface of seeds and the 3D distribution of the temperature at the end of the drying period for sample 2a.

An important step in our research has been the design of an industrial microwave unit, obtained with project PNCDI II Partnerships PNII 51082/2007 "Modern Technology Used for Increasing Stored Seed Quality" coordinated by the University of Oradea and having as partners research institutions, agricultural companies as well as clients.

The industrial microwave system is a drier with mixed hot/room temperature air stream; the seeds movement is determined by a steel screw placed radially on the system's length that, when turning, turns into a magnetic field concentrator. This concentrator determines the homogenization of the temperature field gradient throughout the seed bed and increases the installation yield.

The goal of designing this device was to determine the parameters that form the starting point of a microwave system designed for treating stored cereal grains against pests.

The aim of the microwave system studies was to ensure optimal conditions for the stored seeds in order to help companies in the

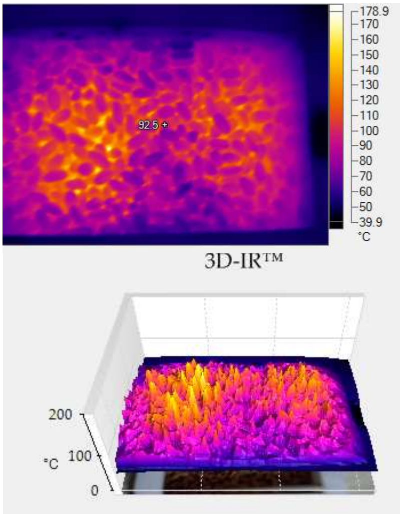

Figure 17. Temperature distribution over the seed bed at the end of the process using the power of the microwaves with hot air stream and the 3D distribution of the temperature.

Table 1. Processed seeds analyze.

Samples	Protein [%]	Gluten [%]	Zeleny [%]	G [%]	T [°C]
Witness Sample	11.9	22	66	95	
1a	11.6	22	62	65	69.6
1b	11.4	22	59	80	50.79
1c	12	26	67	96	55.36
2a	11.4	22	59	98	99.1
2b	11.4	23	63	92	83.73
2c	11.6	23	63	96	129.14

*G = Germination Percentage
T = Average of the temperature measured in the seed bed during the 10 minutes of drying

agricultural area of activity. The microwave system in question was developed in order to achieve the following processes:

- drying seeds to an optimal content of humidity for ensuring a proper maturation process;
- using unconventional protection methods (microwave technologies) for the successful eradication of different types of pests by treating the infested seeds.

5. CONCLUSIONS

The research conducted using the laboratory unit combines the modeling with the experimental results for finding the best combination between applied energy and the material particularity, with the possibility of extending to other cereals.

Table 1 presents results for the analysis of seeds processed in microwaves. The best results are given from sample 1c, where a constant microwave power was maintained at 0.3 W/g with hot airstream. For this sample we had a germination of 96%, protein value of 12% and gluten 26%.

The measured temperature in the seed bed did not go beyond the value of 75.5°C. Of the data presented in the table it can be noticed that the seeds that had been treated in microwave without airstream had a low quality level — samples 1a and 2a.

Analyzing the results obtained it can be said that using the constant microwave power of 0.3 W/g and 0.4 W/g with hot airstream represents the best approach for treating seeds in microwave field, offering good quality and germination.

In the electromagnetic field distribution over the dielectric surface and in the thermal images obtained with the thermal camera, the temperature in seed bed can be noticed — in some points it has higher values that can damage the quality and germination of seeds.

Because of this, it is important that air stream is used for a homogenous temperature distribution in the seed bed and for avoiding the thermal instability and the impossibility of measuring the temperature in each point of the dielectric. Because for samples 1a and 2a, we had contradicting results of the germination rate (see Table 1), for the future, we intend to study these 2 cases.

ACKNOWLEDGMENT

This work was partially supported by the strategic grant POSDRU/88/1.5/S/50783, Project ID50783 (2009), co-financed by the European Social Fund — Investing in People, within the Sectoral Operational Programme Human Resources Development 2007–2013.

This work was cofinanced from the European Social Fund through Sectoral Operational Programme Human Resources Development 2007–2013, project number POSDRU/89/1.5/S/56287 "*Postdoctoral research programs at the forefront of excellence in Information Society technologies and developing products and innovative processes*", partner University of Oradea.

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