Chapter 8
Propagation of Microwave Fields in Grain Material of Various Densities

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8.1 Introduction

The necessity for grain drying of agricultural materials is determined by the necessity to ensure their quality and the period of safe storage. In order to achieve satisfactory level for the manufacturers' economic performance and maintain reasonable consumer prices, it is necessary to use energy-saving equipment. The development of such technological equipment currently involves the use of computer simulation tools, building scalable models, and prototyping of the required equipment. In the case of development of methods of thermal processing of grain materials by methods of RF and microwave effects, we can use such software products of mathematical and visual modeling, like COMSOL, FEMLAB, QW3D, CST Studio, ANSYS, and some others [1–3]. The processes of postharvest handling of grain, which require thermal effects, can be referred drying, disinfection, micronization, and preparation for feeding. All these processes are highly energy intensive.

The cost of postharvest processing is up to 20% on average of the total production costs of grain production and in some cases even more for countries with unfavorable climate [4]. Thus the development of the energy-saving equipment for after-harvesting processing of grain doesn't lose its relevance. The development of scalable models of equipment of the electromagnetic processing gets the special significance in the field of the fast prototyping and the reducing losses due to errors at various stages of development and implementation.

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8.2 Main Part

In the case of dielectric materials with a relatively high factor of dielectric losses exposed to RF and microwave field of sufficient intensity, these materials will absorb the energy of the electric fields by converting electric field energy into thermal energy into the material. This phenomenon is known as dielectric or microwave heating; the term depends on the frequency [5]. The heating level depends on the absorbed power and the characteristics of the material.

The power P, absorbed in the unit of the volume of the dielectric, depends on the dielectric properties and could be calculated using the following equation:

$$P = 2\pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon'' \cdot E^2, \tag{8.1}$$

where P is power, absorbed by the unit of the material; W/m^3; f, frequency of the electromagnetic field; Hz; ε_0, permittivity of vacuum (8854 × 10^{-12} F/m); ε'', loss factor; and E, intensity of the electric field, V/m.

Dielectric heating in the processing of materials is effective in cases where the loss factor is from 2 to 100 [5]. Lower values of it decrease the heating rate, and higher values decrease the depth of penetration of electromagnetic wave in the material layer.

Research Method

The basis for the mathematical description and modeling by software is the system of Maxwell's equations. Software, like COMSOL Multiphysics, FEMLAB, QW3D, CST Studio, and ANSYS, are designed for the solution of these equations by one method or another.

Electrodynamics simulation in HFSS is based on finite element method (FEM). The solution of the boundary problem is sought in the frequency area. The use of the finite element method provides a high degree of universality of numerical algorithms that are highly effective for a wide range of tasks. In our case the object of study is the active zone filled with a layer of grain. Ultrahigh frequency electromagnetic energy supply is carried out from the side with the horn waveguide from the magnetrons.

The article deals with the possibility of representation not only on dense grain layer but the layer with lower density that is typical for fluidized layer, for example. Such way of modeling is important because heat-moisture transfer in this type of layer is characterized by a greater intensity.

In the modeling process of the electromagnetic effects by numerical simulation software of three-dimensional electromagnetic structures, the material which is exposed to a field is usually presented in the form of solid shapes with given properties describing the product at certain values of density, moisture, and other parameters (Fig. 8.1a). In the first stage of simulation, the modeling was performed,

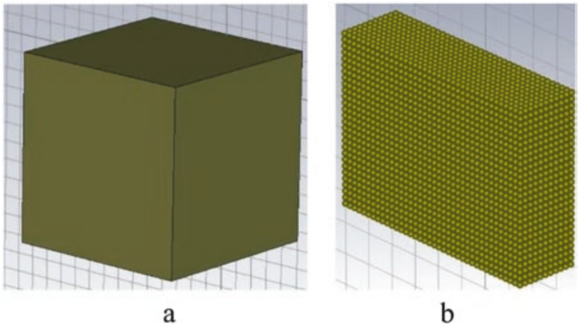

Fig. 8.1 The grain layer representation: (**a**) as a solid structure; (**b**) as a solid layer of substitute forms

and the material was defined with properties that have been reported previously [6–9]. In the case of simulation of field effects on agricultural materials such as grain, feed, and other bulk materials, there is some discrepancy between the properties of the individual grains constituting the layer and the mass of the processed material. It seems very nonrelevant to the description of air gaps and accounting the porosity of layer [6–8]. Thus, it is necessary to consider the option of a presentation layer in the form of volume completely filled with objects that can be represented by the processed material. So, on the second stage of the simulation, the grain in the modeling and mathematical description can be replaced by balls of equivalent diameter. The volume of grain material represented by such method is shown in Fig. 8.1b.

The grain layer after the postharvest handling can be at different densities (dense, loose, fluid, swirl boiling). Measurement of dielectric properties in the cases of the loose layer is almost impossible [6, 9, 10]. For the solving the tasks of modeling and determination of the ε'', the grain layer can be represented with an equivalent volume of grain with a given porosity, which allows to determine the distribution of electromagnetic fields in a layer of predetermined density. Figure 8.2 shows the grain material with different densities.

Each seed can be represented taking into account the inequality distribution of moisture in addition to the submission of the grain layer in the form of a set of seeds. Figure 8.3 shows the seed in form taking into account the equal distribution of moisture and to reflect the changes in humidity from the center of the grains to the surface, which is typical during the drying and disinfection of grain by electrophysical methods of influence.

Properties of grain crops were taken from various sources [6–9] and experimental data [2, 3] for modeling.

Simulations conducted with the grain layer in the form of a set of seeds showed a significant increase in required computer time to obtain results. A representation of the seeds taking into account the unequal humidity, the layers within the grains, led to the need to significantly reduce the number of layers of grains in the simulation.

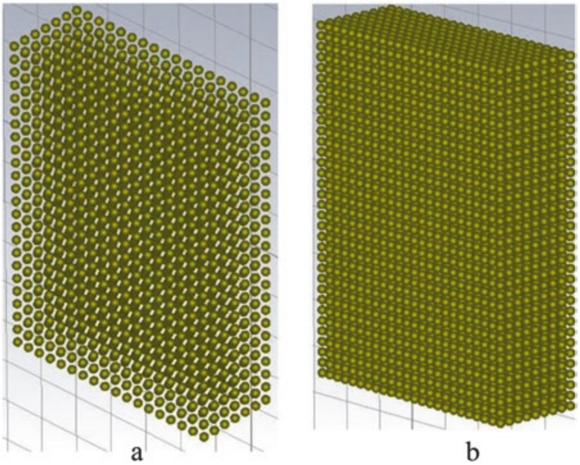

Fig. 8.2 The grain material view: (**a**) soft wheat with humidity 16% and density of the layer 200 kg/m³; (**b**) soft wheat with humidity 16% and density of the layer 500 kg/m³

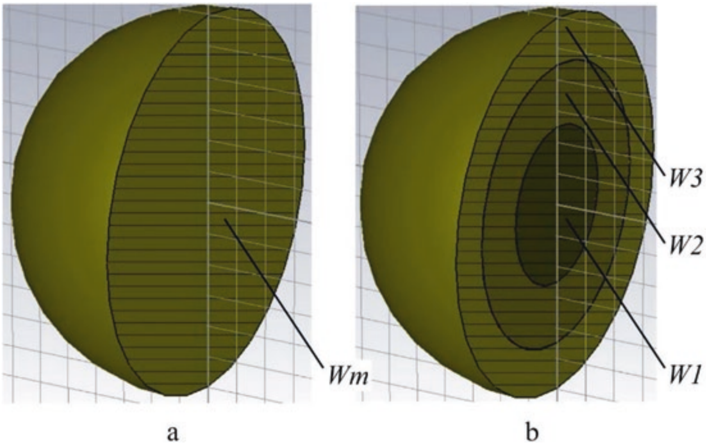

Fig. 8.3 Seed view: (**a**) with equal moisture distribution, *Wm*; (**b**) with variation of the humidity from the center to the surface of the seed, $W1>W2>W3$

Measurement of Dielectric Properties

It is necessary to have reliable data of dielectric properties of the material at the frequency of acting field for quality modeling of propagation of electromagnetic wave in the material. Methods of measurement are different for different frequency ranges. Principles and measurement techniques of microwave dielectric properties were discussed in several reviews [6, 11].

Microwave dielectric property measurement techniques can be classified as measurements of the reflected and absorbed power using resonant or nonresonant systems with open or closed structures to determine the properties of material samples. Also the construction of a dielectric sample holder for concrete materials is important. Method of short-circuited lines to measure the dielectric properties provides a suitable method for many materials, for example, for solid particles and many agricultural materials [6].

Laboratory Setup

Previously developed laboratory setup [3], along with equipment used by the researchers [5, 6], allows to verify the results of the simulation of microwave field distribution in a dense layer. The need to verify the penetration of the electromagnetic field in a slurry layer of grain emerged at this stage, and the need of the measurement of the coefficient of dielectric losses in this layer led to a revision of the existing installation. A modified version of the laboratory setup is schematically represented in Fig. 8.4.

Thus the implementation of the load of the material could be studied both at full and at partial filling of the volume of the microwave-convective processing area. The state of the fluidized or suspended layer is performed by blowing through a layer air with the required speed from the fan. The air flow rate is controlled by vector frequency converter (VFC). The electromagnetic field strength in the layer of material is measured by a device developed and presented earlier [12], and the determination of the coefficient of dielectric loss by analytical methods (8.2), and the coefficient of dielectric loss is determined analytically by formula (8.2); the temperature control of the seeds is measured by thermocouple built into it.

$$\varepsilon'' = \frac{c_m \cdot \rho_m \cdot \Delta T}{5.56 \times 10^{-11} \cdot E^2 \cdot f \cdot \tau}, \tag{8.2}$$

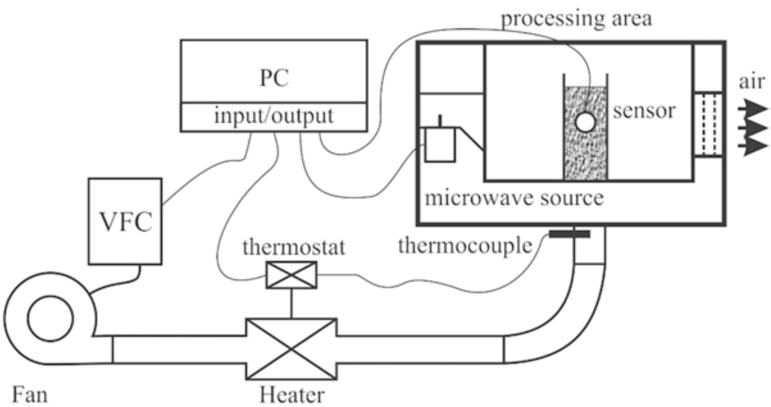

Fig. 8.4 Schematic view of the laboratory setup

where c_m is heat capacity of the material, kJ/kg °C; ρ_m, density of the dry matter of the sample, kg/m^3; ΔT, temperature of the material during process, °C; and τ, time, s.

Measurement Results

Figure 8.5 shows graphs for determining the coefficient of dielectric losses for wheat at a humidity from 11 to 30%.

The obtained results for different densities of the material match the general trend but differ significantly in their level. So, for a dense layer, which corresponds to the density of 660 kg/m^3 in the moisture range 11–30%, the coefficient of dielectric loss changes in the range of 0.18–0.42, for fluidized layer (440 kg/m^3) 0.06–0.15, and for weighted layer (220 kg/m^3) 0.1/0.3. The accuracy of the data for different density levels differs significantly as in the dense layer the error is caused by the used sensors as well as the presence of air gaps in the layer: for fluidized and suspended layers, in addition to the described losses due to the thermal interaction of air with the grain layer and the sensor. The quality of the measurements could be improved using of sensors that are not sensitive to the microwave field, for example, optical, as well as changing in the support method for the desired layer, for example, mechanical.

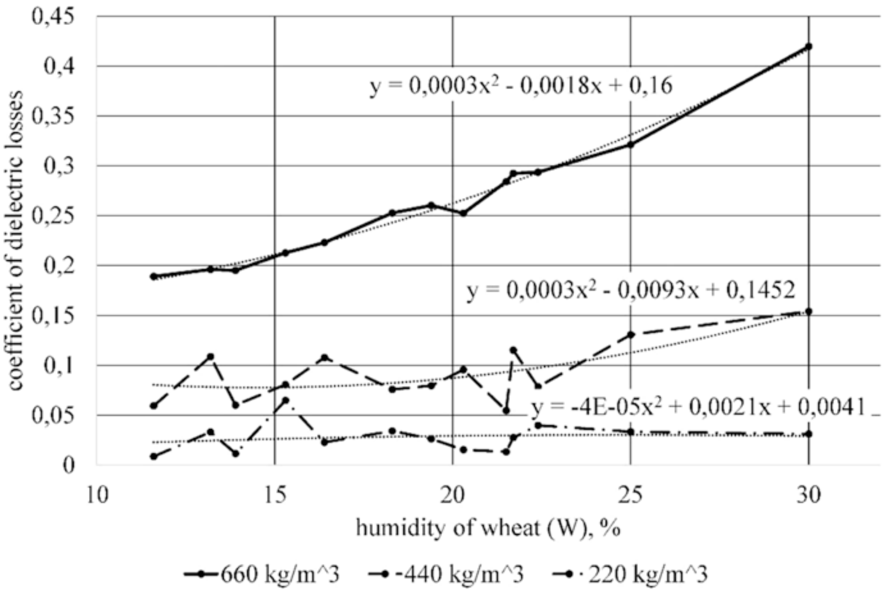

Fig. 8.5 Results of the determination of the coefficient of dielectric losses

Simulation Results

The results of modeling of distribution of electromagnetic field strength in wheat with a moisture content of 16% are presented in Fig. 8.6.

The pattern of distribution of electromagnetic field in the dielectric layer in this case is characterized by the loss (power dissipation) as the wave propagation. The results of modeling show that the distributions of the electromagnetic field of the described variants of implementation of the grain layer are the same, which suggest the possibility of further replacement implementations of the equivalent forms to a solid form. This will significantly reduce the required machine time. Some deviations in the numerical values are due to the lack of considering the influence of reflection waves from the surface of the material and inaccuracy of data on the dielectric properties of materials.

It is also clear from the pattern of distribution of EMF that the selectivity of the heating, that is, typical for areas with higher relative to the rest of the volume of the material humidity (higher dielectric losses), celebrated by many authors [13–17], could be taken into account.

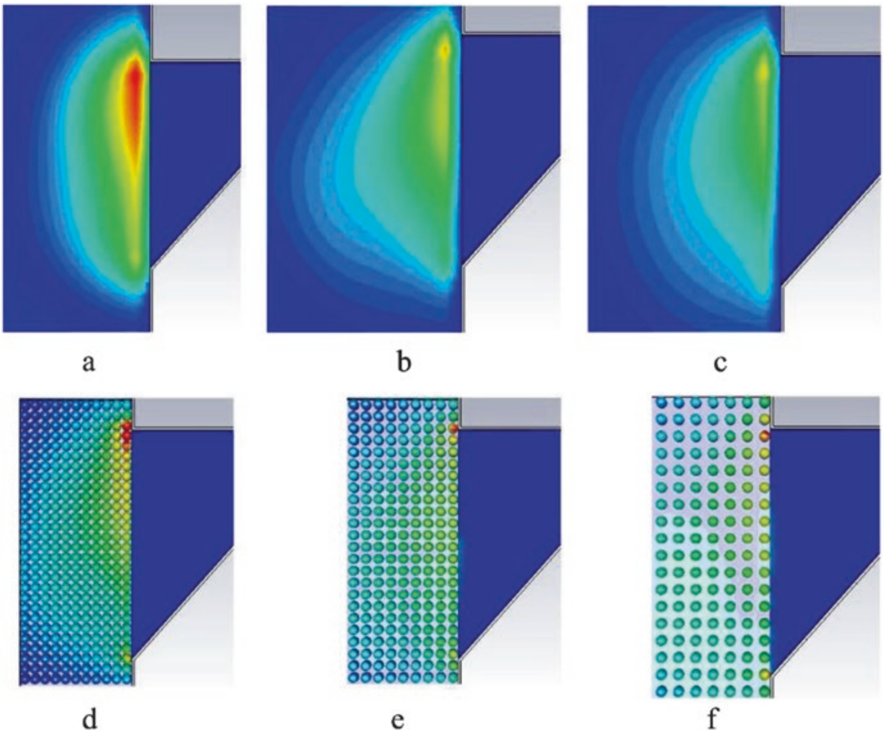

Fig. 8.6 Simulation results for distribution of EMF field strength: (**a**–**c**) in the form of a continuous layer; (**d**–**f**) as a set of spherical grains

8.3 Conclusions

Based on the foregoing, we can conclude the following:

1. Data on the dielectric properties of grains and grain layer should be clarified.
2. It is necessary to conduct experimental studies on the electromagnetic field distribution in the grain layer and compare its results with the results of the numerical experiment.
3. The grain layer in the electrodynamic simulation programs can be implemented as in the solid form and in the form of a set of substitution forms of the source elements (grains).
4. The grain layer should be presented in the continuous form to reduce the intensity of the calculations.
5. Dielectric properties of loose grain layer in the solid form can be obtained through modeling with substitution forms of the appropriate density.

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