Simulation Modeling of the Distribution of Microwave Field Strength in the Grain Layer

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Abstract. To ensure quick prototyping and reduce the possibility of losses caused by errors at various stages of development and implementation of equipment for microwave heating of dielectric materials, the development and simulation of models is of particular importance. The aim of this work is simulation of a slotted waveguide grating for grain drying. The main task of the simulation was to ensure an even distribution of power through each slot. Simulation modeling was carried out using a specialized software package FEKO. To describe the model, an exact calculation method was used - the method of moments; the results were verified. The dependences of the antenna SWR on the width of the slots and the angle of rotation of the slots were investigated and optimal arrangement of slots was chosen. Simulation modeling of field distribution showed that placing the waveguides farther from the container leads to the alignment of the field inhomogeneity, but some part of the radiated power is lost in this case. As the calculation results showed, an increase in the distance between the waveguide and the container with grain did not affect the SWR of the waveguides. It should be noted that in a real situation, the wave character of the field is smoothed out due to heat transfer, which cannot be taken into account in the process of electromagnetic modeling. In addition, the entire spectrum of possible changes in the dielectric parameters of the grain should be investigated in order to analyze the process of wave propagation at high grain moisture. It is also advisable to consider other modifications of the slotted waveguide antennas, which can provide more uniform heating inside the container with grain.

1. Introduction

The high speed and efficiency of microwave heating of dielectrics makes it possible to use the electromagnetic field to heat and dry almost any material containing liquid. Microwave radiation was used in industry for heat treatment and drying of food products since 1960s [1-9]. Drying grain (or other bulk materials) means removing liquid by evaporation.

Microwave heating (dielectric heating) is based on penetration of electromagnetic energy into a material and converting it into thermal energy. The penetration of electromagnetic energy into the material occurs instantly, and the absorption depends on the dielectric properties. The distribution of thermal energy creates conditions for accelerating the diffusion of steam from the inner layers of the material to the peripheral ones, which reduces the energy consumption for the heating process and shortens its duration. Intensification of the grain drying process is one of the promising areas for the use of microwave energy.
The choice of frequency is determined by the characteristics of the material that is necessary to heat. Following frequency ranges are allocated for industrial heating devices in Russia: 433 MHz, 915 MHz, 2450 MHz. Dielectric parameters of grain do not remain constant and depend on the strength of the electric field, frequency of exposure, pressure, temperature, density of the material, moisture, density of the grain mixture, grain grade, presence of pretreatment, presence of impurities and other factors which must be taken into account when designing equipment for electromagnetic processing.

To ensure quick prototyping and reduce the possibility of losses caused by errors at various stages of development and implementation of equipment, the development and simulation of models is of particular importance. It includes the analysis of sensitivity of geometric parameters of equipment in order to determine the accuracy requirements for manufacturing equipment modules. In addition, for correct modeling, information about the dielectric properties of materials and the dependence of these values on density, moisture, etc. are required. Modeling is performed on the basis of electrodynamic simulation. It can be performed in such software products as CST Studio, HFSS, FEKO [10-12].

2. Problem statement and method of solution
The aim of this work is simulation of a slotted waveguide grating for grain drying. The main task of the simulation was to ensure an even distribution of power through each slot. Simulation modeling was carried out using a specialized software package FEKO. To describe the model, an exact calculation method was used - the method of moments; the results were verified. The simulation is performed at a frequency of 2450 MHz. A magnetron with minimum power of 0.75 kW and maximum of 1.5 kW was used as a source. The dielectric constant of the grain is in the range of 2.6 - 3.4, the losses are $\tan \delta = 0.22 \ldots 0.33$.

Waveguide slot antennas were used for grain drying. The energy of electromagnetic field was supplied to the top and bottom sides of the box in which the grain was placed. A waveguide slot antenna is a system of half-wave slots cut in the waveguide wall. Most often, rectangular waveguides with the $H_{10}$ wave are used. It is necessary to ensure uniform irradiation of an extended object, and the radiation power of all slots located on one irradiating waveguide must be the same. When the resonance slot is located on the longitudinal axis of the wide wall, its normalized resistance is zero, and the slot is non-radiating. Thus, by increasing the angle of orientation of the slot relative to the longitudinal axis of the wide wall of the waveguide in the direction of the supplied power, it is possible to implement an irradiation system with uniform microwave power radiation over a considerable length. The method for calculating in-phase multi-slot antennas with a short-circuited end of the line is described in details in [13].

It should be noted that in-phase waveguide-slot antennas are resonant both in the dimensions of the slots and in the distance between them. In the case of mismatch the reflections from each slot in the waveguide add up in phase and the SWR in the supply waveguide sharply increases. The schematic of the inclined slot is shown in Fig. 1.

![Figure 1. Model of a slot in a wide waveguide wall.](image_url)

The slot is placed symmetrically relative to the centerline of the wide wall of the waveguide. Since the slot is excited by longitudinal currents (the transverse currents on both sides of the center line have opposite signs), therefore, the $i$-slot is equivalent to the series resistance
where $\psi$ is the angle between the longitudinal axis of a slot and the centerline of the wide wall of the waveguide. To fulfill the matching condition, it is necessary to ensure the condition

$$R_n = 1,$$

where $n$ is the number of slots in the slotted waveguide grating.

Figure 2 shows the dependence of the normalized resistance of the slot on the inclination angle of the slot relative to the transversely oriented slot in the wide wall of the waveguide.

$$R = 0.131 \frac{\lambda^2}{\lambda_n \alpha b} \left(f_1(\psi) \sin(\psi) + \frac{\lambda_n}{2\alpha} f_1(\psi) \cos(\psi) \right)^2,$$

$$f_1(\psi) = \frac{\cos \frac{\pi \xi}{1-\xi^2}}{1-\gamma}, \quad f_2(\psi) = \frac{\cos \frac{\pi \gamma}{1-\gamma^2}}{1-\gamma^2}, \quad \xi = \frac{\lambda}{\lambda_0} \cos \psi - \frac{\lambda}{2\alpha} \sin \psi, \quad \gamma = \frac{\lambda}{\lambda_0} \cos \psi + \frac{\lambda}{2\alpha} \sin \psi,$$

where $\psi$ is the angle between the longitudinal axis of a slot and the centerline of the wide wall of the waveguide. To fulfill the matching condition, it is necessary to ensure the condition

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Computer simulation in the FEKO program was used to calculate the distribution of the electromagnetic field and specific absorbed power in the dielectric volume. To solve the problem, the method of moments embedded in the program was used. To reduce computational requirements, the solution to the problem was performed in two stages, based on decomposition. At the first stage, a solution to the antenna problem of the field distribution in the aperture was obtained, that is, the currents were calculated on a rectangular area corresponding to the radiating wall of the waveguide. At the second stage, using a rectangular platform with the already known current distribution as the source of the electromagnetic field, the distribution of absorbed power in the chamber volume was calculated.

Fig. 3 shows the dependence of the normalized resistance of the slot on the inclination angle of the slot relative to the transverse slot in the wide wall of the waveguide for an inhomogeneous waveguide, in which the waveguide height decreases linearly with distance from the source (the waveguide is narrowing along the vertical). The dependences of the normalized resistance make it possible to choose the slope angle of the slots which ensures the matching condition both in homogeneous waveguide and in converging waveguide.

**Figure 2.** Dependence of the normalized resistance of the slot on the inclination of the slot relative to the transverse slot in the wide wall of the waveguide.
Figure 3. Dependence of the normalized resistance of the slot on the angle of inclination of the slot relative to the transverse slot in the wide wall of the waveguide and the height of the waveguide $b$.

The investigated model of a slotted waveguide antenna with 28 slots is shown in Fig. 4.

Figure 4. Slotted waveguide antenna model in FEKO software.

For the model the dependences of the antenna SWR on the width of the slots and the angle of rotation of the slots were investigated (Fig. 5). The models were verified by comparing the results obtained with different meshing of surface elements.

Figure 5. Dependence of the SWR on the slot width and on the inclination angle (the angle is measured from the transverse orientation of the slots).
As can be seen from the presented dependences, an increase in the width of the slots leads to an almost linear increase in the SWR in the waveguide. Therefore, for further calculations, the slot width was taken to be 3 mm. The dependence of the SWR on the angle of rotation of the slots has a strongly marked minimum. In this case, a change in the angle of inclination from 75° to 83° leads to a change in SWR in from 1.1 to 3.

3. Discussion of results
Fig. 6 shows the distributions of the electric field strength and power flux density in the longitudinal plane. The greatest unevenness is observed in the center of the slotted waveguide antenna. It can be eliminated by changing the angles of rotation of the slots numbered 12 – 17. It should be noted that such a solution will lead to an increase in the antenna SWR, but for the investigated model the SWR does not exceed 1.7. Thus, all 28 slots of the antenna radiate, while the SWR in the waveguide path is not worse than 1.7.

Figure 6. Distribution of the electric field strength in the longitudinal plane of the waveguide.

Structurally, the grain processing equipment is a container with grain, which is subjected to microwave processing using two slotted waveguide antennas located on opposite sides. The antennas are shifted relative to each other in order to create a more uniform distribution in the volume. The investigated model is shown in Fig. 7. The distance between the container with grain and the waveguides \( h_{gap} \) was \( \lambda_a/8, \lambda_a/4 \), where \( \lambda_a \) is the wavelength in the waveguide. The width of the slots is taken equal to 0.3 cm, the inclination angle of the slots is 82.25°. The SWR does not exceed 1.7 for both cases of the arrangement of the waveguides with respect to the container with the grain.

Figure 7. Model of grain processing by microwave radiation generated by two slotted waveguide antennas.

Particular attention should be paid to the choice of the height of a container with grain. The non-uniformity of the power propagation through the thickness of the processed material is caused by losses in the layers of the material with distance from the source. The main characteristic of this unevenness can be the depth of field penetration, which is determined by the dependence:
\[ \tau = \frac{\lambda}{2\pi \sqrt{\varepsilon' \tan \delta}} \]

where \( \lambda \) is the wavelength, m; \( \varepsilon' \) is a dielectric constant of material, \( \tan \delta \) is loss tangent. The penetration depth of the field shows at what thickness the field weakens by a factor of \( e \) times. Fig. 8 shows the dependence of the thickness of the skin layer on losses in the material and the dielectric constant of the material. The size of the skin layer is the determining parameter when choosing the size of the container with grain.

![Figure 8](image)

**Figure 8.** Dependence of the thickness of the skin layer on losses in the material and the dielectric constant of the material.

The results of electromagnetic modeling of field strengths and specific absorbed power (W/kg) inside a container with grain in horizontal and vertical planes are shown below. The arrangement of two waveguides shifted relative to each other allows to get a more uniform heating of the grain inside the volume. The paper investigated the distributions of the electric field and specific absorbed power in the vertical and horizontal planes oriented with respect to the slots of the waveguide-slot antenna. Calculations showed that the removal of the waveguide from the surface of the container leads to a more uniform distribution of the electric field with a simultaneous decrease in its level. Figures 9 - 10 show the distributions of electric field strength and specific absorbed power in horizontal plane in the middle of the container with grain at different distances between the waveguide and the container with grain.

Thus, the given model of the slotted waveguide antenna allows heating the grain. To improve the penetration of the electromagnetic wave, it is to place a matching layer of dielectric material with the parameters \( \sqrt{\varepsilon'} \) between the waveguide and the container to improve the matching with the grain volume. The given examples of field distribution show that there is an uneven distribution of the field over the container volume. Placing the waveguides farther from the container leads to the alignment of the field inhomogeneity, but some part of the radiated power is lost in this case. As the calculation results showed, an increase in the distance between the waveguide and the container with grain did not affect the SWR of the waveguides.
4. Conclusion
Simulation modeling was carried out using a specialized software package FEKO. The main task of the simulation was to ensure an even distribution of power through each slot for uniform heating of grain. The dependences of the antenna SWR on the width of the slots and the angle of rotation of the slots were investigated and optimal arrangement of slots was chosen.

Simulation modeling of field distribution showed that placing the waveguides farther from the container leads to the alignment of the field inhomogeneity, but some part of the radiated power is lost in this case. As the calculation results showed, an increase in the distance between the waveguide and the container with grain did not affect the SWR of the waveguides.

It should be noted that in a real situation, the wave character of the field is smoothed out due to heat transfer, which cannot be taken into account in the process of electromagnetic modeling. In addition, the entire spectrum of possible changes in the dielectric parameters of the grain should be investigated in order to analyze the process of wave propagation at high grain moisture. It is also advisable to consider other modifications of the slotted waveguide antennas, which can provide more uniform heating inside the container with grain.

5. References
[1] Budnikov D A 2014 Investigation of the dynamic properties of the grain layer under microwave convective influence Innovacii v sel’skom hozjajstve 4 pp 92-96 (in Russian)
[2] Budnikov D A 2015 Planning an experiment to control the change in the complex dielectric index of the grain layer under microwave convective action Vestnik VNIIM 4 pp 39-42 (in Russian)
[3] Budnikov D A 2013 Absorption of the microwave electromagnetic field by agricultural materials Vestnik VIJeSH 2 pp 38-40 (in Russian)
[4] Cymbal A A, Budnikov D A 2016 Dielectric properties of cereals Vestnik VNIIMZh 4(24) (in Russian)
[5] Budnikov D A 2015 Study of the distribution of the microwave field strength in the grain layer Inzhenernyj vestnik Dona 3 (in Russian)
[6] Baptista F, Silva L L and de Visser C 2013 Energy Efficiency in Agriculture 5th International Congress on Energy and Environment Engineering and Management (Lisbon, Portugal)
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