Microwave absorption and reflection properties of a composite dielectric absorber

I Shorstkii and M Sosnin

1Kuban State University of Technology, Department of Technological equipment and life-support systems, Krasnaya Street 135, Krasnodar, Russian Federation

Email: thegector@mail.ru

Abstract. Microwave assisted technologies and its application are widely used in different research fields. One of the main difficulty of this area is to design a treatment chamber. The aim of this paper is to measure power absorption and calculate average surface microwave power density of composite dielectric materials, based on plant particles. Obtained microwave-absorbing characteristics of composite plant material can be used in microwave assisted processes and high-performance microwave treatment chambers design to facilitate the research in microwave assisted drying and extraction. The research includes experiments with different positioning of the composite materials from reflective metal screen inside the chamber-waveguide.

1. Introduction

Applying novel, alternative processing techniques, such as microwave heating, microwave assisted drying and pulsed microwave treatment appearing in food technologies requiring microwave absorption properties of different plant composite materials. To predict heating rates and describe the behaviour of plant materials when applying different electrical and electromagnetic fields is very important to know absorption material characteristics. An emerging new drying technologies such as assisted by pulsed microwave (PW) [1], pulsed electric field (PEF) [2-3] or by electrohydrodynamics (EHD) [4] requires full materials properties knowledge: dielectric constants and absorption properties in wide frequency range. In find literature only few research groups reported information about incident and absorbed power during microwave drying process, probably because of the limitations of experimental systems. The purpose of this work is to investigate the microwave absorption properties of sunflower crop in radio frequency range.

2. Theory

When electric fields are applying to a dielectric composite material the formation of several electric dipoles takes place, which align themselves according to the orientation of the applied electric field. A dielectric in such a state is called polarized for a small volume, in which polarization is considered. Polar dielectrics are characterized by polar molecules, in which when the external electric field has not applied the centers of positive and negative charges do not match with each other. An external electric field tends polar molecules orientation in the field direction. This orientation is hampered by the chaotic thermal molecules movement. As a result, the combined action of the thermal motion of molecules and
applying electric field results in the resulting dipole electric moments orientation of the molecules along the field, increasing when electric field increasing and decreasing temperature.

Polarization in non-polar dielectrics is due to the displacement of the electron shells relative to the nuclei. The model of the effective center of positive charges is represented as a cloud of an atom consisting of nuclei, and the model of the effective center of negative charges is represented as a cloud consisting of electronic orbits. Between these effective centers there is a distance characterized as a dipole arm. When external electric field \( E_0 \) applied there is a displacement of these centers relative to each other. If the external field \( E_0 \) varies with frequency, and causes forced oscillations of the electron shells, then a resonance is observed as a result of the coincidence of the frequency of the external electric field and the frequency of the forced oscillations of the displacement between the effective centers in the dielectric.

![Figure 1.](image)

Polarization in polar (a) and non-polar (b) dielectric materials and summary possible paths of incident electromagnetic wave in material (c)

The main interest in microwave assisted drying or microwave assisted extraction in heating by Joule effect, which can be find from reciprocal influence on the electromagnetic fields causes the absorbed energy. The property of a material to absorb, reflect, and transmit from an impact falling from outside radiation depends on the properties of the material itself and the radiation flux. The radiation flux is characterized by the frequency and angle at which the surface of the studied material is irradiated. When incident wave path on a surface it can be absorbed by material, transmitted and reflected immediately or internal reflected back again. Three main components of incident energy \( E_i \) distribution inside the material: absorbed \( E_a \), transmitted \( E_t \) and reflected \( E_r \) energies and their relationship according to energy conservation law can be expressed as [7]:

\[
E_i = E_a + E_t + E_r
\]  

or in percentage:

\[
100\% = A\% + T\% + R\%
\]

where \( A\% = E_a/E_i \times 100 \); \( T\% = E_t/E_i \times 100 \); \( R\% = E_r/E_i \times 100 \).

Under conditions of hemispherical irradiation of the material, its reflectivity and transmittance, always receives hemispherical radiation of energy into the surrounding space. The absorption energy can be determined from the energy conservation law and calculate according to expression:

\[
E_a = 1 - (E_t + E_r)
\]

The attenuation can be expressed in dB according to [8]:

\[
Attenuation(dB) = 10\log \frac{E_i}{E_j}
\]

The result of strong radiation scattering is high reflectivity, which increases with increasing material density. The loose packaging structures of the material in the treatment chamber reduce the reflectivity of the material. In dielectric composite materials, the main properties that enable them to be applicable...
as microwave absorber are the dissipation factor of energy and dielectric constant. Usually, the dielectric microwave absorbers change their dielectric properties through the thickness, which directly relies with industrial drying or extraction process. For higher frequencies and higher dielectric constant values, greater reflected energy occurs from an untreated dielectric surface which directly relies with treatment chamber size and capacity of the process [9]. In this case, it is important to emphasize that for design high-performance microwave treatment chambers to facilitate the research in microwave absorption characteristics is quite important.

3. Materials and methods

3.1. Material preparation
Crushed sunflower crop (CSC) was used for measurements. CSC had a crushed grain with a fraction of 1-2 mm³. To obtain a sample of composite material with required size and to study microwave absorbance characteristics paraffin in volume ration 1:1 was added to the CSC medium. Obtained composition was brought to the melting point using electric oven and mixed. After composite material had cooled and solidified it was cut into three parallelepipeds with 28 × 12 × 25, 23 × 10 × 45 and 28 × 12 × 5 mm size.

3.2. Experimental
For microwave-absorbing characteristics measurements the prepared composite materials were evaluated by absorbance measurements using two waveguide techniques, first P2-59 in a frequency range of 5.6 to 8.3 GHz and second P2-61 in a frequency range of 8.15 to 12.1 GHz. Metallic plate as a perfect reflector with 0% of attenuation was used.

Different protocols of sample position relative to the aluminum plate were compared (figure 2):
- Protocol A: tight contact of sample (28x12x25) and aluminum plate;
- Protocol B: sample position with air gap L=10 mm from aluminum plate;
- Protocol C: sample (28x12x25) with absorber material (-25dB);
- Protocol D: tight contact of sample (28x12x5) and aluminum plate.

![Figure 2. Experiment protocols with different sample size and position](image)

The surface analysis of the prepared plant composite samples was observed using SEM JOUL 6300 microscope directly after preparation.

4. Results and discussion
CSC surface morphology with a fraction of 1-2 mm³ is shown at figure 3. Material model presented as a form of spherical bodies surrounded by an air envelope, which can be reduced if the material is compressed.
Figure 3. SEM image of SCS with compact particles structure.

Figure 4 shows the reflectivity curve in frequency range 5.6-8.3 GHz of the processed SCS composite material based (protocol A). Solid black line shows transmitted characterization of the composite material and dotted line reflection loss. By the condition of the experiment, the metal plate acts as a reflector. Incident wave goes through the sample, met with a metal plate and reflect in the opposite direction. The reflected wave interferes with the internal reflected wave. Thus, the reflection loss, according to the measurement results, is the sum of two waves. This value cannot be used for absorption coefficient calculation. For an objective assessment of the reflection loss coefficient RL, we use the reflection loss Rp (%) according to the results of the experiment for Protocol C from figure 4.

Figure 4. Microwave reflection loss RL and transmittance of SCS composite material sample versus frequency for protocol A, B, C and D.

In protocol C we used an absorber with absorption coefficient of -25 dB. This device completely absorbs incident waves that has passed through the sample. The reflection coefficient Rp (%) from the sample surface according to the results of the experiment in Table 1, for a frequency of 6.0 GHz is 25%.
Table 1. Parameters of microwave absorbance properties in range from 5.6 to 12.1 GHz for protocols A, B, C and D.

| Frequency, GHz | Transmission (%) | Reflection (%) | Absorption (%) |
|---------------|-----------------|----------------|----------------|
|               | A               | A              | B              | C              | D              | A              |
| 5.6           | 50              | 25             | 31             | 23             | 39             | 25             |
| 7.2           | 59              | 22             | 85             | 22             | 23             | 19             |
| 8.3           | 75              | 2              | 56             | 1.25           | 20             | 20             |
| 8.9           | 51              | 22             | 27             |                |                |                |
| 10.6          | 47              | 18             |                |                |                |                |
| 12.1          | 51              | 0.3            |                |                |                | 48.7           |

From obtained experimental data we have found that the SCS composite material presents mostly transmitter (~50%), reflector (~25%) and absorbed (~25%) behavior, similar to protocol A and C. Data from protocol A suggest composite material use as absorber at high-frequency range. Absorbance properties frequency dependence can be used in treatment chamber and its geometrical size design. It is also observed that air gap between sample and reflector assigns distinct behaviors of electromagnetic radiation attenuation by the prepared samples.

Sample with 25 mm thicknesses (protocol A and C) presents low reflection loss, nearly 2 dB for 8.3 and 12.1 GHz and high attenuation; this result suggest that the material processed with bigger thicknesses is susceptible to microwave treatment. The observed behavior is attributed to the heterogeneity of the water content of the crushed sunflower crop.

The sample on protocol A shows higher table values of attenuation in range from 19-49% in the frequency range of 5.6-12.1 GHz. The absorbed energy value is close to 19% at the frequency of 7.2 GHz. From this point it is observed that absorbance increases in frequency range between 9 and 12 GHz and get a maximum value 48.7% of incident energy at 12.1 GHz. Absorption and reflection properties present interesting results with possibilities in different applications in radio frequency material treatments, such as microwave heating, microwave drying etc.

This result suggests that the absorbing characteristic is directly related to the material thicknesses and position relative to the plate, which can change the attenuation, consequently, the absorption of the incident radiation.

5. Conclusion
Crushed sunflower crop showed absorption properties depending on geometrical size, its position relative to the metal plate installed in the waveguide, as well as on the EMI radiation frequency.

The density of the material is represented as bulk with a loose structure. Samples with geometrical dimensions of 28x12x25 mm, exhibits maximum absorption properties at a level of 20-30% with a frequency of the electromagnetic wave in range 5.6-8.3 GHz. The sample has direct contact with absorber. The air gap between the sample and absorber increased the reflection coefficient, which leads to additional dissipation of the power of EMI, but attenuation coefficient A(%) has decreased.

Samples with 28x12x5 mm size have a high reflectance characteristics as a result of the interference of two waves reflected from sample and from the metal plate. Attenuation coefficient for protocol D was minimal. With an increase EMI frequency range from 8.15 to 12.05 GHz, the transmittance of the samples increased, and the reflection coefficient decreased. This indicates absorption properties increases. Absorption properties of all SCS composite materials at low frequency range are in low range. Increases of the absorption coefficient at low frequencies of microwave radiation is necessary to modify the parameters of the material. Obtained results offer an effective way to design high-performance microwave treatment chambers to facilitate the research in microwave assisted drying and extraction and microwave absorption.
Acknowledgments
The reported research was funded by Russian Foundation for Basic Research and the government of the region of the Russian Federation, grant № 18-38-00448.

Reference
[1] Kumar C, Joardder M H, Farrell T W, Millar G J and Karim M A 2016 Dry. Technol. 34 962-73
[2] Parniakov O, Bals O, Lebovka N and Vorobiev E 2016 In. Food Science & Emer. Technol. 35 52-7
[3] Shorstkii I A and Khudykov D A 2018 Proceedings of VSUET 80 49-54
[4] Martynenko A and Zheng W 2016 J. of Food Eng. 168 215-22
[5] Constant T, Moyne C and Perre’ P 1996 AIChE J 42 359–67
[6] Feng H 2000 Microwave drying of particulate foods in a spouted bed (Washington: Washington State University)
[7] Folgueras L C, Nohara E L, Faez R and Rezende M C 2007 Mat. Res. 10 95-9
[8] Shorstkii I and Yakovlev N 2019 Mater. Res. Express 6 046104
[9] Hourquebie P and Olmedo L 1994 Synt. Met. 65 19-26