URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Wideband measurement of dielectric properties of powder materials: developing an experimental set-up

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Abstract

Knowledge of dielectric properties of materials is at the basis of the application of microwaves as non-destructive and non-invasive tools for quality evaluation of foods. In this contribution, the development of an experimental framework to characterize on a wide frequency range dielectric properties of powder food is proposed. The used methodologies include the open-ended coaxial probe technique and a waveguide system, the former being inherently a wideband technique but suffering from the typology of material under test, the latter being a medium-band technique. Examples of measured materials are reported, with particular reference to the measurement of sugar.

1 Introduction

Quality control of food to discover possible contaminations and/or adulteration is becoming increasingly important in the food industry. Several techniques can be used to try to detect foreign bodies as small plastic/glass/paper fragments in real time during the packaging chain. Examples are X-rays [1] or fluorescence imaging [2]. Among the possible techniques that can be used for non invasively monitoring the food composition without interrupting the production chain, electromagnetic (EM) imaging, with particular reference to microwave imaging (MWI) can be cited [3,4]. MWI reconstructs the images of the dielectric properties of the domain under test by processing the EM field scattered by the different objects once enlightened by an incident EM field. To this end, an array of antennas, alternatively used to transmit or receive the signal is used, and detailed knowledge of the dielectric properties of the scanned materials is needed.

In this contribution, an experimental framework developed to measure the dielectric properties of powder materials, such as sugar, flour, coffee, and so on, is presented. The experimental set-up foresees the use of two different measurement techniques, one based on the open-ended coaxial probe, the other based on rectangular waveguides. Both techniques have advantages and disadvantages for the foreseen application, so that their combined use can strengthen the achieved results. In the following, the two measurement techniques will be presented, and preliminary results will be shown.

2 Methodology

The open-ended coaxial probe is the most suited sensor to achieve wideband measurement of dielectric properties [5]. The technique is based on the measurement of the reflection coefficient of a coaxial line, whose open end is immersed or placed in contact with the material under test (MUT). The reflection coefficient, masured by way of a Vector Network Analyser (VNA), depends on the dielectric properties of the MUT. Accordingly, the material complex permittivity can be recovered by making use of appropriate models of the electromagnetic field at the open end of the coaxial probe. The simplest models are based on a lumped-element circuit, which can include or not radiation effects. In the first case, the method can be applied up to tens of GHz, in the latter the reconstruction is accurate up to a few GHz [5].

In this paper, the High Temperature Probe (HTP) of Keysight (Santa Rosa, CA, USA) connected to the PNA AGILENT E8363C (Agilent Santa Clara, CA, USA) was used. The probe has a useful bandwidth up to 20 GHz, and it is recommended for the measurements of the dielectric permittivity of liquids, semi-solids, and solid materials with flat surfaces. The permittivity of the MUT was reconstructed with customized algorithms implementing both the lumped element model without the radiation effect [5,6] and with it [7,8]. Before the measurement, calibration was carried out measuring the reflection coefficient of the probe when left in air, closed with the shorting block available with the HTP, and when immersed in deionized water. To apply the algorithm including the radiation effects [7,8], a second calibration liquid is needed which was isopropilic alcool.

The open-ended coaxial probe shows accuracies as high as 5% [9,10] when the MUT diameter is greater than 20 mm and its thickness is greater than $20/\sqrt{|\varepsilon^*|}$ mm. Additionally, if a granular material is under measure, the granule size shold be lower than 0.3 mm [Keysight]. Besides the dimensions of the MUT, to achieve best accuracy, a proper contact between the probe and the MUT

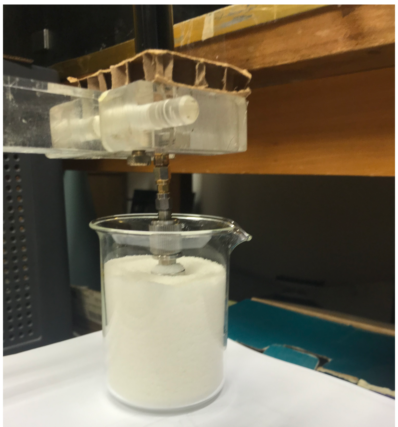

Figure 1. High Temperature Probe immersed in the sugar powder

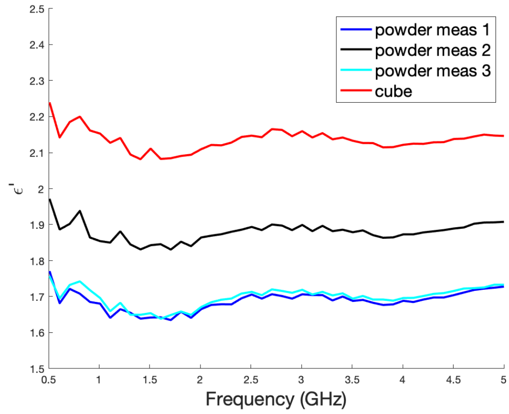

Figure 2. Open-ended probe measurements of the relative permittivity of sugar power and sugar cube (reconstruction model without radiation effects)

should be achieved. In fact, the presence of small air bubbles at the open end of the probe can greatly influence the accuracy of the result.

Since in this work powder or granular materials are concerned, to verify the accuracy of the measurements performed with the open-ended probe technique, an additional measurement set-up was used. In particular, the WR430 waveguide was used, whose transversal dimensions are about 109 mm × 55 mm, and whose frequency band lies in the 1.7–2.6-GHz region. The set-up is made by two coaxial to rectangular waveguide transitions (N-type to WR430), two standard WR430 waveguide sections, and a sample holder, 10 cm long. To allow the insertion of granular materials in the sample holder, two pressurization windows are present, directly connected to the sample holder ends [11]. Calibration is performed by way of the thru-reflect-line (TRL) method, including the short circuit (i.e., a metallic end plate), and a waveguide section of known length. To perform the measurements, the coaxial to rectangular waveguide transitions were connected to the Agilent E8363C vector network analyzer, equipped with Agilent 85071E permittivity measurement software [12]. To reconstruct the dielectric properties of the MUT, the "fast transmission" algorithm was used. It consist in an iterative technique that estimates permittivity and then minimizes the difference between the transmission parameter (S_{21}) value calculated from that permittivity and the measured values until the error is less than the expected system performance.

3 Results and Discussion

Figure 1 shows the HTP placed in contact with the sugar power. From the figure it is evident the modification of the sugar surface following the contanct between the MUT and the probe. These modifications tend to induce the presence of air gaps between the open-end of the probe and the material, which would negatively impact on the reliability of the measurement. To evidence these difficulties, Figure 2 shows the relative permittivity of sugar as reconstructed by way of the lumped element circuit without the inclusion of the radiation effects [6] achieved from 3 different measurements of the sugar powder and one measurement of a sugar cube. From the figure it is immediately derived that the measurements by way of the open probe technique are greatly influenced by the contact realized between the probe and the material. Indeed, the measurement of the sugar cube, which is a compact structure, gives higher values of the relative permittivity in the whole frequency band considered, thus evidencing that the measurement of the sugar powder were influenced by the presence of small air gaps between the probe and the sugar.

To validate the achieved results and to quantify the material density, the use of a different set-up has be considered. As a matter of fact, the use of a rectangular waveguide, in which the quantity of material can be carefully controlled, thus controlling its density, would allow to classify measurements reporting different values for the dielectric properties. However, rectangular waveguides show a smaller bandwidth than the open probe technique, so that,

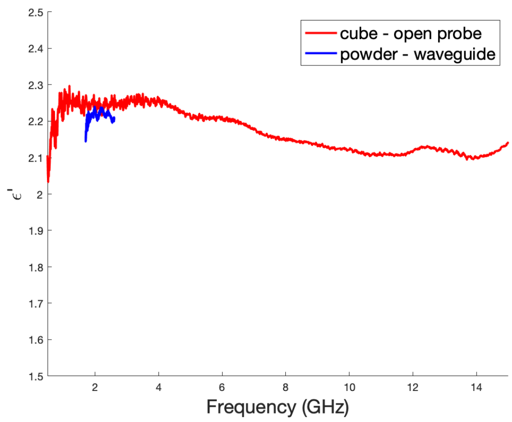

Figure 3. Rrelative permittivity of sugar measured by the open-ended technique (reconstruction model including radiation effects) and by the waveguide system

they cannot be used to cover the whole MW spectrum. Given the flatness showed by the measured curves in Figure 3, which exclude the presence of relaxation phenomena in the studied frequency band, the combination of the two techniques can be used: the waveguide one to classify the properly measured samples, and the open probe to give information on a wide frequency band.

4 Conclusion and Future Work

This paper presents a general framework to obtain the dielectric properties of powder or granular food on a wide frequency band by combining two measurement techniques, the open-ended coaxial probe and the rectangular waveguide. Results showed the influence on the data measured by way of the open ended probe of the contact between the open end and the material under test. The proposal is to use the rectangular waveguide measured data to discriminate among the measurements performed by the open-ended coaxial probe.
Future work foresees the use of an additional waveguide system, operating at higher frequencies, to help in the verification of the measured properties. Then, other materials will be tested.

5 Acknowledgements

This work was supported by PRIN Broadband Electromagnetic Sensing Technologies for Food quality and security assessment (BEST-Food grant n. 20179FLH4A) funded from the Italian Ministry for University and Research.

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