Determination of multicomponent media permittivity by high-frequency method

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Abstract. The problem of determining the multicomponent media equivalent permittivity by a high-frequency dielectric method was considered. Analytic calculations of the medium equivalent permittivity by changing the frequency of the measuring high-frequency generator were presented. The variation of the volume ratio measurements results of the mixture components caused by the different components distribution in the volume was determined. The results of an experimental study in laboratory conditions of the dielectric permittivity measurer physical model were presented.

1. Introduction

A high-frequency method is one of the methods for measuring the dielectric characteristics of the mixed composition media. The essence of the method lies in the fact that the investigated material sample is placed in the action field of the capacitor, which is included in the circuit of the high-frequency generator. The deviation of the generator frequency from the base frequency, corresponding to the sample of a known composition, is an informative parameter carrying information about the dielectric characteristics of the investigated material. Varieties of this method are widely represented in the literature [1-12] and have shown their effectiveness, in particular, at moisture control of soil [1-7], fibrous materials [4, 6] and raw wood.

The equivalent permittivity of the multicomponent medium can be used as a parameter characterizing its substance composition. In particular, this method is widely used for the moisture content control of liquid and solid media [1-3]. However, it is known that the results of measurements can significantly change due to various factors [3, 6]. In this paper, the authors set the task of assessing the impact on the measurement result of the dielectrics components distribution in the volume of the investigated medium.

2. Analytical calculations of the measuring cell capacity

The output frequency of the LC generator is defined as:

\[ f = \frac{1}{2\pi\sqrt{L_k C_x}} \]

where \( L_k \) is the inductance of the circuit; \( C_x \) – scheme equivalent capacity.

When

\[ C_x = \frac{1}{4\pi^2 L f^2}. \]  

(1)
The capacitance of the circuit contains both a component proportional to the permittivity of the medium and a component of it. Taking this into account, we can write down that:

\[ C_x = A\varepsilon_r + B \] (2)

where \( \varepsilon_r \) – the sample dielectric permittivity, \( A, B \) – constant coefficients.

Let the results of the generator frequencies measurements \( f_1 \) and \( f_2 \), corresponding to samples with known dielectric permittivities \( \varepsilon_1 \) and \( \varepsilon_2 \), be known; then the capacities will be equal to:

\[ C_1 = \frac{1}{4\pi^2 L f_1^2} ; \] (3)

\[ C_2 = \frac{1}{4\pi^2 L f_2^2} . \] (4)

Considering the formula (2), we obtain the following system of equations:

\[
\begin{cases}
C_1 = A\varepsilon_1 + B \\
C_2 = A\varepsilon_2 + B
\end{cases}
\]

solving which we obtain:

\[ A = \frac{C_2 - C_1}{\varepsilon_2 - \varepsilon_1} , \] (5)

\[ B = \frac{C_1\varepsilon_2 - C_2\varepsilon_1}{\varepsilon_2 - \varepsilon_1} . \] (6)

Thus, by determining the parameters \( A \) and \( B \) with the help of samples with known properties, it is possible to determine the sample permittivity of multicomponent composition.

From the formula (1), we obtain:

\[ \varepsilon = \frac{C_x - B}{A} , \] (7)

expressing capacity through the generator frequency, while taking into account (1), we obtain:

\[ \varepsilon = \frac{1}{4\pi^2 LA} \cdot \frac{1}{f^2} \cdot \frac{B}{A} . \] (8)

3. Analytical calculations of the measurements variation

The sample capacity for the same components ratio can take different values, the variation range of which can be determined as follows. Let a sample of volume \( V \) consist of two dielectrics with volumes \( V_1 \) and \( V_2 \) and dielectric permittivities \( \varepsilon_1 \) and \( \varepsilon_2 \), such that \( \varepsilon_1 > \varepsilon_2 \).

Let us denote the volume content of the components, respectively:

\[ w_1 = \frac{V_1}{V_1 + V_2} , \]

\[ w_2 = \frac{V_1}{V_1 + V_2} . \]

It’s obvious that:

\[ w_1 + w_2 = 1 , \]

as

\[ V = V_1 + V_2 . \]

In the general case, the components can be arbitrarily distributed in the volume \( V \). However, the smallest (Figure 1a) and the largest (Figure 1b) values of the measuring cell capacitance would correspond to two limiting cases.
Figure 1. The moisture distribution in the measuring cell and the corresponding equivalent circuit

In the first case (Figure 1a):

\[ C' = C'_1 + C'_2, \]  

in the second (Figure 1b):

\[ C'' = C''_1 + C''_2. \]  

As is known, the capacitance of a flat capacitor is determined by the formula:

\[ C_1 = \frac{\varepsilon_1 S}{d}. \]

For the components of the capacitance \( C' \), the area occupied by both components is equal, and the thickness of the layers is proportional to their volume content, so:

\[ C'_1 = \frac{\varepsilon_1 S}{w_1} = C_1 w_1^{-1} \]

and

\[ C'_2 = \frac{\varepsilon_2 S}{w_2} = C_2 w_2^{-1}. \]

Then:

\[ C' = \left(\frac{w_1}{C_1} + \frac{w_2}{C_2}\right)^{-1}. \]

For the components of the capacitance \( C'' \), the area occupied by the components is proportional to their volume content, and the thickness of the layers is the same, so:

\[ C''_1 = \frac{\varepsilon_1 S w_1}{d} = C_1 w_1 \]

and

\[ C''_2 = \frac{\varepsilon_2 S w_2}{d} = C_2 w_2. \]

Then:

\[ C'' = C_1 + C_2. \]

As a result, the cell capacity at the same volume content of components can vary in the range

\[ C' \leq C \leq C''. \]

Due to the different distribution of components in the volume, the permittivity of the sample will also vary.
4. Experimental studies

To determine the variation range of the dielectric constant during measuring the sample moisture content by the generator method, experimental studies of various multicomponent liquid and dry media were performed. As a sensor a coplanar sensor made of fiberglass, containing 3 pairs of vertically arranged electrodes, produced by copper etching, was used. The width of the electrodes is 3 mm, the distance between the electrodes is 2 mm. The electrodes were placed in a container with a sample to a depth of 70 mm. To prevent the flow of through currents between the electrodes, they were isolated from the sample by a layer of polymer film.

The well-known circuit shown in Figure 2 was used as the generator, the generator is implemented by a two-point scheme on field effect transistors VT1, VT2, the repeater scheme is implemented on transistors VT3, VT4. The UNI-T UT30F multimeter in the frequency measurement mode was used as a secondary instrument.

Measurements were performed while the sensor was in the air $\varepsilon_1 = 1$, $f_1 = 6.13$ MHz, then — when the sensor was placed in water $\varepsilon_2 = 80$, $f_2 = 4.35$ MHz. Capacities calculated by the formula (2) are $C_1 = 66.97$ pF, $C_2 = 133.86$ pF; hence, according to the formulas (8)-(9), $A = 0.85$, $B = 66.12$.

As an example, the results of experimental studies carried out with oil, to which water of a mass fraction from 0 to 10% was added, were presented. In this case, the dielectric constant of the mixture was calculated from formula (10) with the substitution of experimental values into it. The dielectric permittivity values obtained experimentally, as well as their linear approximation (the green line), are shown in Figure 3.

Also in Figure 3, the dielectric permeability calculated by the formula (9) at substitution of the capacity determined by the formula (13) is shown in red color, and blue – during substitution in it, the capacity determined by the formula (14).
It can be seen from the graphs that the obtained analytical expressions adequately describe the processes in the measuring system. Significant (more than 10%) variation of the mixture dielectric permittivity caused by the different distribution of the mixture components. The authors believe that the increase in the accuracy of the dielectric high-frequency measurement method is possible only with the active mixing of the sample, ensuring the uniformity of the moisture distribution in the sample volume.

In order to verify this statement, the generator frequency deviation measurements were additionally performed during the absence (Figure 5a) and the presence (Figure 5b) of mixing.

As can be seen from the graphs presented in figure 5, the mixing of the samples makes the distribution of the components more uniform in volume, which reduces the variation of the readings.

5. Conclusion
The theoretical results obtained by the authors are confirmed by the experimental studies data, which allows speaking about their adequacy. The given formulas allow one to determine the multicomponent dielectric permittivity and to estimate the measurement results variation of the dielectric components volume content depending on the distribution of the latter in the sample volume.
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