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CRITICAL ANALYSIS OF FORMULAE FOR THE CALCULATION OF THE ELECTRICAL PARAMETERS OF HUMID MATERIAL

KRITIČNA ANALIZA FORMULE ZA IZRAČUN ELEKTRIČNIH PARAMETROV VLAŽNOSTI MATERIALA

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Abstract

A comparative analysis of conventional calculation expressions for the determination of the electric parameters of humid material has been done. Their disadvantages have been determined, and the errors of their use for calculation of electrical characteristics of a specific material (zinc cake) have been determined. A means of improving the considered calculation expressions has been proposed.

Povzetek

Predstavljena je primerjalna analiza klasičnih računskih izrazov za določitev električnih parametrov vlažnosti materiala. Njihove pomanjkljivosti so nakazale na napake, ki se pojavljajo pri uporabi izračunov električnih karakteristik pri realnem materialu cinkove pogače. Predlagan je način izboljšave obravnavanih računskih izrazov.

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1 INTRODUCTION

In many technological processes from coal preparation to grain processing, it is necessary to control material humidity. Essentially, its values determine the energy costs required for preparation of the output product. In its turn, the humidity of the material, irrespective of its chemical composition, as a rule, is determined from expressions taking into account the relation of its values to the values of dielectric permittivity of the corresponding processed material.

At present, several models (calculation expressions for description of the properties) of humid materials are known, *[1-15]*. They are mainly intended for liquid-water systems, as these systems provide a possibility to find a determined relation between dielectric permittivity (DP) and humidity *W*.

Fundamentals of theoretical calculations of DP for liquid-water systems have been established by several authors *[4-8, 11-13]*, but some of them show the relation between DP and humidity implicitly (Tables 1-3, where ε_d, ε_w are the dielectric permittivities of the "dry" phase and water, respectively). As the authors are not aware of more recent research in this field, they considered it necessary to perform a critical analysis of the available calculation expressions.

2 BASIC MATERIAL OF THE RESEARCH

Let us perform a comparative analysis of the models given in Tables 1–3. Obviously, in Table 1 formula 1.1 can only be applied when the water layer is parallel to impacting electrical (or electromagnetic) field without mixing with the dry phase. Formulae 1.3–1.6 seem to be meant for calculations at low values of humidity as at $W \to 1$ they result in a significant error, which is stated in *[2]*.

As to formulae 2.1 and 2.2, it can be noted that they, as well as formula 1.1, seem to be correct for separate layers of water and dry material, but arbitrarily oriented in relation to the electromagnetic field. This is their advantage over formula 1.1. However, in all the other aspects they are rather conditional for the real pattern of location of water in the material.

One of the basic faults of formulae 3.1-3.7 consists in implicit dependences of ε on W. In *[2]*, this fault is eliminated by expansion of formulae 3.1-3.7 in series by degrees W, which is of the form:

for formulae 3.1, 3.2

$$\frac{\varepsilon}{\varepsilon_d} = 1 + 3W\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d} + 9W^2\left(\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\right)^2\frac{\varepsilon_w}{\varepsilon_w + 2\varepsilon_d} + \\ + 27W^3\left(\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\right)^3\frac{\varepsilon_w(\varepsilon_w - \varepsilon_d)}{(\varepsilon_w + 2\varepsilon_d)^2} + \ldots, \tag{1}$$

for formula 3.3

$$\frac{\varepsilon}{\varepsilon_d} = 1 + 3W\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\left[1 + W\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d} + W^2\left(\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\right)^2 + \ldots\right], \tag{2}$$

Table 1: *Material dielectric permittivity ε explicit direct dependences on humidity W*

No.	Author(s) of the formulae	Dependence type and formulae number
1	Silberstein, Newton	$\varepsilon = \varepsilon_d(1-W)+\varepsilon_w W$ (1.1)
2	Lorenz	$\varepsilon = \frac{\varepsilon_d(\varepsilon_w+2)+2W(\varepsilon_w-\varepsilon_d)}{\varepsilon_w+2+W(\varepsilon_w-\varepsilon_d)}$ (1.2)
3	Odolevskii (for statistic systems)	$\varepsilon = \frac{(2-3W)\varepsilon_d+(3W-1)\varepsilon_w}{4} + \sqrt{\left[\frac{(2-3W)\varepsilon_d+(3W-1)\varepsilon_w}{4}\right]^2+\frac{\varepsilon_d\varepsilon_w}{2}}$ (1.3)
4	Odolevskii (for matrix systems)	$\varepsilon = \varepsilon_d\left[1+\frac{3W}{\frac{1-W}{3}+\frac{\varepsilon_d}{\varepsilon_w-\varepsilon_d}}\right]$ (1.4)
5	Botcher	$\varepsilon = \varepsilon_d\left(1+3W\frac{\varepsilon_w-\varepsilon_d}{\varepsilon_w+2\varepsilon_d}\right)$ (1.5)
6	Fradkina	$\varepsilon = \varepsilon_d\frac{\sqrt[3]{(1-W)^2}(\varepsilon_w+2\varepsilon_d)^2+2W(\varepsilon_w-\varepsilon_d)^2}{\sqrt[3]{1-W}(\varepsilon_w+2\varepsilon_d)^2+(\varepsilon_w-\varepsilon_d)^2}$ (1.6)
7	Reynolds, Hugh	$\varepsilon = \varepsilon_d+\varepsilon_d W(\varepsilon_w-\varepsilon_d)(\varepsilon_d+A(\varepsilon_w-\varepsilon_d))^{-1}$ (1.7)

Table 2: *Material dielectric permittivity explicit indirect dependences on humidity*

No.	Author(s) of the formulae	Dependence type and formulae number
1	Beer	$\sqrt{\varepsilon} = W\sqrt{\varepsilon_w}+(1-W)\sqrt{\varepsilon_d}$ (2.1)
2	Lichtenecker	$lg\varepsilon = W lg\varepsilon_w+(1-W)lg\varepsilon_d$ (2.2)
3	Relay (with Runge's correction)	$\frac{\varepsilon}{\varepsilon_d} = 1-\frac{3W}{W+\frac{2\varepsilon_d+\varepsilon_w}{\varepsilon_d-\varepsilon_w}+0.523\frac{\varepsilon_d-\varepsilon_w}{\frac{3}{4}\varepsilon_d+\varepsilon_w}W^{1/3}}$ (2.3)

for formula 3.4

$$\frac{\varepsilon}{\varepsilon_d} = 1 + 3W\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d} \times \\ \times\left[1 + W\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\left(1 + 0.1\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\right) + W^2\left(\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\right)^2 + \left(1 + 0.2\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\right)\ldots\right], \quad (3)$$

for formula 3.5

$$\frac{\varepsilon}{\varepsilon_d} = 1 + 3W\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d} \times \\ \times\left[1 + W\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\left(1 + 0.1\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d} + 0.36\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\right)^2 + \ldots\right], \quad (4)$$

formula 3.6 is expanded as

$$\frac{\varepsilon}{\varepsilon_d} = 1 + 2.19W\left(1 + \frac{0.37}{\varepsilon_d}\right)\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d} \times \\ \times\left[1 + W\left(0.5 + 1.1\left(\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\right)^2 \times \frac{1 + \frac{0.74}{\varepsilon_d} - 3\left(\frac{\varepsilon_d + 0.37}{\varepsilon_w - \varepsilon_d}\right)^2}{1 + \frac{0.37}{\varepsilon_d}}\right) + \ldots\right], \quad (5)$$

and formula 3.7

$$\frac{\varepsilon}{\varepsilon_d} = 1 + 3W\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\left[1 + 2W\frac{\varepsilon_w - \varepsilon_d}{\varepsilon_w + 2\varepsilon_d} \times \frac{2\varepsilon_w + \varepsilon_d}{\varepsilon_w + 2\varepsilon_d}\right]. \quad (6)$$

However, it should be noted that expressions (1)–(6) can be applied to limited values of humidity, because when condition $W \to 1$ is met, some series diverge. So, at $W = 0.9$, $\varepsilon_w = 80$, $\varepsilon_d = 2$ from (1) we obtain

$$\varepsilon = 2 + 5.01 + 11.97 + 27.87 + \ldots,$$

and from (3)

$$\varepsilon = 2 + 5.01 + 4.58 + 4.15 + \ldots$$

At the same time in formula (6), restricted by three members, under the same conditions, values ε approaching $\varepsilon_в$ are not achieved: $\varepsilon = 23.18$.

Table 3: *Material dielectric permittivity implicit dependences on humidity*

No.	Author(s) of the formulae	Dependence type and formulae number
1	Landauer	$W\frac{\varepsilon_w-\varepsilon}{\varepsilon_w+2\varepsilon_d}+(1-W)\frac{\varepsilon_d-\varepsilon}{\varepsilon_w+2\varepsilon_d}=0$ (3.1)
2	Botcher	$\frac{\varepsilon-\varepsilon_d}{3\varepsilon}=W\frac{\varepsilon_w-\varepsilon}{\varepsilon_w+2\varepsilon}$ (3.2)
3	Clausius-Mossotti, Lorentz, Viner	$\frac{\varepsilon-\varepsilon_d}{\varepsilon+2\varepsilon_d}=W\frac{\varepsilon_w-\varepsilon_d}{\varepsilon_w+2\varepsilon_d}$ (3.3)
4	Piecara	$\frac{\varepsilon-\varepsilon_d}{\varepsilon+2\varepsilon_d}=W\frac{\varepsilon_w-\varepsilon_d}{\varepsilon_w+2\varepsilon_d}+0.1W^2\left(\frac{\varepsilon_w-\varepsilon_d}{\varepsilon_w+2\varepsilon_d}\right)^2$ (3.4)
5	Tareev	$\frac{\varepsilon-\varepsilon_d}{\varepsilon+2\varepsilon_d}=W\frac{\varepsilon_w-\varepsilon_d}{\varepsilon_w+2\varepsilon_d}\times \times\left(1+W\left(0.1\left(\frac{\varepsilon_w-\varepsilon_d}{\varepsilon_w+2\varepsilon_d}\right)^2+0.038\left(\frac{\varepsilon_w-\varepsilon_d}{\varepsilon_w+2\varepsilon_d}\right)^3\right)\right)$ (3.5)
6	Kubo-Nakamuro	$3\varepsilon_w lg\frac{\varepsilon_w-\varepsilon}{\varepsilon_w-\varepsilon_d}-(\varepsilon_w-0.74)lg\frac{\varepsilon+0.37}{\varepsilon_w+0.37}= =(2.2\varepsilon_w+0.81)lg(1-W)$ (3.6)
7	Bruggeman	$\frac{\varepsilon_w-\varepsilon}{\varepsilon_w-\varepsilon_d}\sqrt[3]{\frac{\varepsilon_d}{\varepsilon}}=1-W$ (3.7)

Some authors *[1, 2]* mention that many formulae provide much better approximation to experimental results, if the form of the water-material connection dependence on its dielectric permittivity is taken into consideration. Therefore, in the domain of low humidity it is proposed to assume $\varepsilon_w=31$ *[10]*, which makes it possible to considerably improve the accuracy of formula 2.1, but the following remains undetermined: condition of applicability of equality $\varepsilon_w=80$ and in what correlation (i.e. what part of water has $\varepsilon_w=31$, and what part has $\varepsilon_w=80$) they are to be taken.

In *[16]*, a model is proposed in the form of evenly distributed particles of the hard phase in an air matrix. As humidity increases, water forces air out and water dielectric permittivity varies from $\varepsilon_w=3$ (for the chemically bound one) to $\varepsilon_w=80$ (for the free one) in the function of humidity content and according to the law

$$\varepsilon_w=80-77e^{-\alpha_1 u}, \quad (7)$$

where α_1 – constant coefficient, dependent on the type of dry material e.g. for clay of a certain type $\alpha_1 = 0.44$.

The analysis of formulae in Tables 1–3 reveals that many of them, especially those from Table 3, practically coincide at low humidities ($W \approx 0 \div 0.1$) and correspond rather well to the experiment. At high humidity values divergence increases both between the formulae and in relation to the experiment. For example, let us compare the results of calculation of ε by formulae given in tables 1–3, with the results of experimental determination of zinc concentrate ε at the "Electrozinc" plant (Vladikavkaz, Russia). The measurements were carried out in laboratories by Q meters of E9-4 and E9-5a types. Three samples of concentrate (No. 1, 2, 3) different as to the content of zinc and other components by some percent were under control, *[17].* The results of measurements and calculations are given in Tables 4–6.

In Tables 4–6, the numbers in brackets in the column corresponding to formula 1.6 are values obtained according to formula 1.6 after its expansion into series according to *[12].* Coefficient A in formula 1.7, depending on relation of the ellipsoidal particle axes lengths and its orientation in relation to the field, was assumed equal to 1/3, as zinc concentrate particles are mainly of a spherical shape.

Values ε in Tables 4–6 are rounded off to the second figure, as the stated error of experimental determination of ε is about 5%. Therefore, it is not necessary to calculate ε more accurately and calculation was carried out with three exact figures afterwards rounded off to the second figure.

A comparison of experimental data with the calculated ones demonstrates the following:

1. Results obtained by the groups of formulae 2.3, 3.3, 3.4, 3.5, 3.7 and 1.3, 2.2, 3.1, 3.2, as well as 1.5, 1.6, 1.7, 3.6 at the humidity of 0.04, practically coincide (up to the error of rounding) and are within the range of experimental values close to higher (77 MHz) frequency.
2. At the humidity of 0.08 and, a fortiori, of 0.12, coincidence can be seen in the groups of formulae. However, divergence between the groups is much bigger (up to 0.2÷0.3), and divergence with the experiment grows up to scores of percent even at higher frequencies.
3. Formula 1.2 gives explicitly low results in the completely calculated range of humidity.
4. Value obtained by formulae 1.2, 1.4, 2.1, though considerably different from each other, are mainly within the range of experimental data. Values obtained by formula 1.1 are within the values for the frequency range of units of MHz and less, and by formulae 1.4 and 2.1, within the order of tens of MHz.
5. All the given formulae provide results not depending on frequency, which does not correspond at all to real parameters of all bulk materials analysed by the author (coal and coal charge of Donetsk, Vorkuta and Ekibastuz coal basins; zinc and lead ores; some soils in Luhansk and Moscow regions, as well as in Krasnodar territory; cereals; potassium and other salts). Many authors *[18-20]* also confirm this conclusion.
6. Almost all the given formulae fail to take into account the shape of bulk particles (apart from 1.7), and package density influence ε_d and enters the formulae mainly linearly. At the same time, in practice, according to *[14]*, bulk materials ε nonlinear dependence on density takes place.

Table 4: *Results of measurements and calculations of zinc concentrate ε (sample No. 1) depending on humidity W and frequency f at εd=2.2*

No.	*W*, r.u.	*f*, MHz	ε experimental	Values of ε, calculated by relevant formulae in tables 1–3															
				1.1	1.2	1.3	1.4	1.5	1.6	1.7	2.1	2.2	2.3	3.1	3.2	3.3	3.4	3.5	3.6	3.7
1	0.04	2.00 7.25 21.0 77.0	5.3 4.1 3.9 2.9	5.3	2.4	2.5	3.0	2.4	1.2 (2.4)	2.4	3.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.4	2.5
2	0.08	2.00 7.25 21.0 77.0	6.0 5.3 4.4 3.5	8.4	2.5	2.8	3.8	2.7	1.3 (2.7)	2.7	4.3	2.9	2.7	2.8	2.8	2.8	2.8	2.8	2.7	2.8
3	0.12	2.00 7.25 21.0 77.0	11 8.0 6.4 4.5	11.5	2.7	3.5	4.7	2.9	1.4 (2.9)	2.9	5.7	3.4	3.0	3.2	3.2	3.0	3.0	3.0	2.9	3.0

Table 5: *Results of measurements and calculations of zinc concentrate ε (sample No. 2) in the function of humidity W and frequency f at ε_d=2.9*

No.	*W*, r.u.	*f*, MHz	ε experimental	Values of ε, calculated by relevant formulae in tables 1–3															
				1.1	1.2	1.3	1.4	1.5	1.6	1.7	2.1	2.2	2.3	3.1	3.2	3.3	3.4	3.5	3.6	3.7
1	0.04	2.00 7.25 21.0 77.0	4.9 4.5 3.2 3.1	6.0	3.1	3.2	3.9	3.2	1.7 (3.2)	3.2	4.0	3.3	3.2	3.2	3.2	3.2	3.2	3.2	3.1	3.2
2	0.08	2.00 7.25 21.0 77.0	6.8 5.3 4.7 3.5	9.1	3.3	3.7	4.9	3.5	1.8 (3.6)	3.5	5.2	3.8	3.6	3.7	3.7	3.6	3.6	3.6	3.5	3.6
3	0.12	2.00 7.25 21.0 77.0	– 13 8.7 5.1	12	3.5	4.2	6.1	3.8	1.8 (4.1)	3.8	6.6	4.3	4.0	4.2	4.2	4.0	4.0	3.9	3.9	4.0

Table 6: *Results of measurements and calculations of zinc concentrate ε (sample No. 3) in the function of humidity W and frequency f at εd=2.8*

No.	*W*, r.u.	*f*, MHz	ε experimental	Values of ε, calculated by relevant formulae in tables 1–3															
				1.1	1.2	1.3	1.4	1.5	1.6	1.7	2.1	2.2	2.3	3.1	3.2	3.3	3.4	3.5	3.6	3.7
1	0.04	2.00 7.25 21.0 77.0	5.6 4.5 3.9 3.1	5.9	3.0	3.1	3.7	3.1	1.6 (3.1)	3.1	3.9	3.2	3.1	3.1	3.1	3.1	3.1	3.1	3.0	3.1
2	0.08	2.00 7.25 21.0 77.0	8.8 7.2 5.5 3.9	9.0	3.2	3.5	4.8	3.4	1.8 (3.5)	3.4	5.1	3.7	3.5	3.6	3.6	3.5	3.5	3.5	3.4	3.5
3	0.12	2.00 7.25 21.0 77.0	13 12 9.2 6.3	12	3.4	4.1	5.9	3.7	1.8 (3.9)	3.7	6.5	4.2	3.8	4.1	4.1	3.8	3.8	3.8	3.7	3.8

7. Influence of bulk material chemical composition is also expressed via ε_d, though at high humidity ε dependence on it grows.
8. Dependence of ε on humidity is practically linear in all the formulae, though in real bulk materials it is not quite so.

Convergence of calculated and experimental data in the bulk materials electrical theory developed in [3] is better. The authors of this theory managed to obtain root-mean-square deviation of calculated and experimental results of no more than 3–5% for a number of materials (coal charge for coking, wheat, zinc cake, some ordinary coals and soil types and other materials) at the humidity of no more than 10–15%. However, at high humidities, especially for soils, zinc cake and ordinary coals, at the frequencies of units of MHz and less, divergence made scores of percent and, in some cases, hundreds of percent.

Sometimes, experimental values of ε exceeded ε values for water, which cannot be explained by the error of the experiment. Thus, the theory proposed in *[3]*, does not provide satisfactory explanation either.

3 CONCLUSIONS

Based on the above, it can be stated that existing mathematical models of humid bulk materials do not reflect the parameters and characteristics of the real material quite adequately. First, they provide results independent of frequency; they do not take into account the shape of bulk material particles and the nonlinear character of packing density influence. Consequently, they need considerable improvement, including the possibility of changing the approaches.

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