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APPLICATION FOR DATA PROCESSING AND ANALYSIS OF MEASUREMENT DATA OF THE CONCENTRATION-DEPENDENT DIELECTRIC PERMITTIVITY OF TWO-COMPONENT COMPOSITES

Abstract. The article presents the results of using computer technologies for data processing and analysis in dielectric measurements, structural control, and properties of polymer composite materials and heterogeneous dielectrics. The algorithm used allows the identification of the structure of non-homogeneous dielectrics with conductive inclusions by analyzing the experimental concentration dependence of static dielectric permittivity. It helps to determine whether their structure corresponds to known models of matrix systems or statistical mixtures. The developed application can be seen as part of the software for creating an automated system for scientific research in the field of electronics of heterogeneous structures and materials, and it can also be used autonomously.

Keywords: automation of dielectric research, data processing, heterogeneous dielectrics, application, Mathcad program, interface design.

Problem statement. The processing of experimental data to obtain information about the physical and physicochemical properties of various materials is one of the key tasks in their research and technical application. This procedure is usually associated with the need to use appropriate mathematical models and perform non-trivial mathematical operations.

The use of computer technologies for these purposes, in particular, intelligent information-measuring systems [1–5], significantly reduces the labor intensity of the process and improves the accuracy of the results obtained.

One of the areas where such an approach is particularly relevant is the processing and analysis of experimental data in dielectric research and the control of properties of ceramic varistor and polymer composite materials and heterogeneous dielectrics in general [6–11].

An important aspect in the development of such semiconductor heterogeneous materials is the study of the influence of their structure, the properties of the polymer matrix, and the filler, as well as the physicochemical interaction between them, on the electrophysical properties of the composites in general [12–14].

Dielectric spectroscopy for this type of two-component systems is one of the most effective methods for studying the structural features and mechanisms of electrical conductivity formation.

A particular interest lies in studying the dependence of electrical conductivity and dielectric permittivity on the concentration (volume fraction) of the filler, as this allows the anal-

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ysis of percolation phenomena and effects related to the formation of transition phases with different physical properties from the original components of the composites [15–17].

Research objective. The aim of the research is to create an application for automating the processing and analysis of experimental concentration dependence of static dielectric permittivity of heterogeneous dielectrics with conductive inclusions in order to determine whether their structure corresponds to matrix systems or statistical mixtures.

The algorithm implemented in the application is based on the use of the most well-known models for describing the dielectric properties of two-component dielectrics: the Bruggemann-Hanai model for matrix systems and the Boettcher-Hsu model for statistical mixtures [15, 18].

Presentation of the main material of the research. To develop an effective algorithm for processing and analysis, it is necessary to analyze the physical foundations of the process.

Within the framework of the matrix system model (Bruggemann-Hanai) [4,12,14], the concentration dependence of the static dielectric permittivity of a two-component system ε_{ml} with conductive inclusions in an insulating environment (matrix) is described using the following expression:

$$\varepsilon_{ml} = \varepsilon_d \cdot (1 - p_V)^{-1/\ A} \tag{1}$$

where ε_d , p_V and A are the relative dielectric permittivity of the matrix, volume fraction, and depolarization factor of the conductive particles, respectively. It is generally assumed that the particles have an ellipsoidal shape, and *A* can vary from 0 to 1 [19–21]. In the case of unordered inhomogeneous (isotropic) systems, the particles are considered spherical, and i *A* = 1/3.

For a statistical mixture, the dependence of static dielectric permittivity ε_{sl} on the volume fraction is described by the Boettcher-Hsu model [18], and it can be written as [20,22]:

$$\varepsilon_{sl} = \varepsilon_d \cdot p_{th} \cdot (p_{th} - p_V)^{-1} \tag{2}$$

where p_{th}— is the threshold (percolation) value of the volume fraction of the conducting component [14].

As can be seen from (2), as $p_V \rightarrow p_{th}$, the low-frequency dielectric permittivity of the statistical mixture ε_{sl} increases infinitely.

For a two-component statistical mixture with spherical particles in the Boettcher-Hsu model, the theoretical value of $p_{th}\ =\ 1/3$ [20,22].

It should be noted that in a number of known theoretical models of electrical conductivity in two-component media, the percolation threshold is determined by an expression of the form $p_{th}\ = z/2$, where z — is the number of bonds between homogeneous particles located at the nodes of a particular lattice (the bond model) [23]. Depending on the degree of order and physical properties, it has been shown that the percolation threshold value p_{th} can vary from 0,05 to 0,6 [23-26].

The unknown parameters in (1) and (2) are *A* and p_{th}. The condition for applying either of the models in a specific real situation is the possibility of approximating the experimental dependence $\varepsilon_{lE}(p_{VE})$ in the coordinates $[log(1-p_{VE});\ log(\varepsilon_{lE})]$ or $[log(p_{th}-p_{VE});\ log(\varepsilon_{lE})]$ with a straight line [25,27].

The description of the main operations of the developed algorithm can be outlined as follows:

1. For applying the least squares method [28], the experimental data for the concentration dependence of the low-frequency dielectric permittivity are presented in relative coordinates such as $[y_E^i = log(\varepsilon_{lE}^i/\varepsilon_{lE}^0);\ x_{E1}^i = log(1-p_{VE}^i)]$ and $[y_E^i = log(\varepsilon_{lE}^i/\varepsilon_{lE}^0);\ x_{E2}^i = log(p_{th}-p_{VE}^i)]$. Here, ε_{lE}^i and p_{VE}^i - the experimental values (*i* = 0, 1, … *n*-1; *n* — is the number of experimental points).
2. The theoretical approximating expressions (1) and (2) are rewritten as:

$$y_1(p_V, A) = -log[(1-p_V)/(1-p_V^0)]/A \tag{3}$$

$$y_2(p_V, p_{th}) = -log[(p_{th}-p_V)/(p_{th}-p_V^0)] \tag{4}$$

3. To determine the unknown parameters A та p_{th} the following target functions must be minimized:

$$F_k(a_k) = \sum_{i=0}^{n-1}\left[y_E^i - y_k(p_{VE}^i, a_k)\right]^2 \tag{5}$$

where *k* = 1–2; $a_1 = A$ та $a_2 = p_{th}$.

The quality of the approximation can be measured by the root mean square error of the approximation divided by the empirical mean value (variation coefficient), which is determined for each section of the relaxation dependence by the formula:

$$v_k = \frac{\sqrt{F_k(a_k)/(n-1)}}{\sum_{i=0}^{n-1} y_E^i/n_k} \tag{6}$$

4. To choose the optimal model, the condition of minimizing the corresponding root mean square error is applied, for example, the rule for the *k*-th kinetic dependence is as follows:

IF $v_{min} = min(v_k)$, THEN the *k*-th model is selected.

To implement this algorithm, the well-known and widely used mathematical software package Mathcad [29] was chosen as the main tool. The program’s user interface was developed using Visual Studio tools. Specifically, the monitor for the package was created using C# within a Windows Forms Application project type. As previously mentioned, the computational algorithm’s application module consists primarily of Mathcad documents, specifically version 15, which are utilized for performing the necessary calculations and operations.

In addition, the application supports a range of universal tools that allow users to work with various file formats, including .xlsx (Excel spreadsheets) and .dat (text data files). The results of computations are stored in text files, and the content of these files is then displayed on the screen in the appropriate form field. The results are added to the ListBox element for better organization and easier access by the user [30,31].

For easy navigation between different sections of the application, buttons (Button) are used, allowing the user to move seamlessly from one part of the program to another. The user interface is designed with the understanding that the application integrates different software products, which work together to provide a comprehensive solution. It includes various service functions to assist users with data processing and analysis. These functions and the overall system layout are clearly depicted in Figure 1.

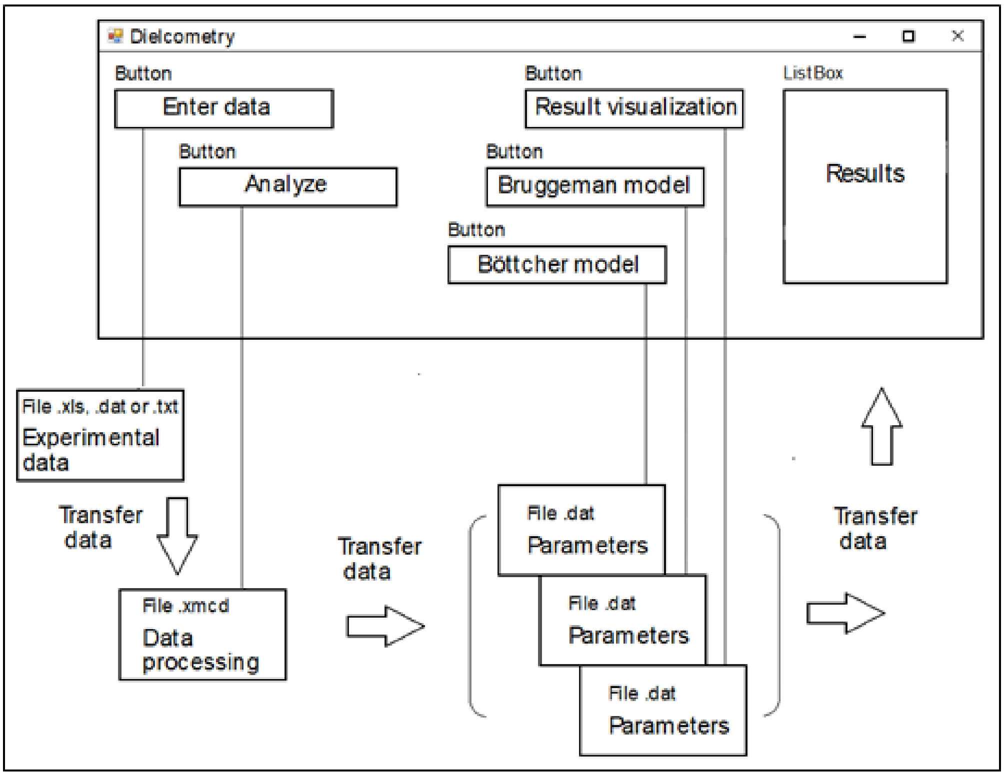

Figure 1 – Main user interface window and application operation diagram

The algorithm to interact with the user interface can be described by the following steps:

1. Data input. The operator uploads the corresponding table of experimental measurement data on the concentration dependence of static dielectric permeability into an Excel spreadsheet (transition to the data file window by clicking the "Enter date" button).

2. Calculation in the Mathcad software package of the model parameters for the specified dependence for a given factor value and transferring them to the result analysis text file (transition to the Mathcad software module window by clicking the "Analyze" button). Additionally, the conversion and transfer of output data to a separate text file is performed automatically.

3. Displaying the results in the ListBox field (clicking the "Result visualization" button).

Furthermore, the main window contains the buttons "Bruggeman model" and "Bottcher model," which allow, if necessary, to check the correctness of the entered data and review the obtained values of the model parameters and relative modeling errors, respectively.

Conclusions. A variant of the implementation of computer analysis of measurement data of the concentration dependence of dielectric permeability in two-component composites is presented, aimed at obtaining information about their structural features.

As a result of this processing, it is possible to obtain information about the structure model that best describes the electrical properties of the studied heterogeneous material, as well as determine the optimal parameters of the selected model (depolarization factor for particles of the component with higher electrical conductivity for the matrix system or percolation threshold for the statistical mixture).

The developed application can be considered as part of the software for an automated system for scientific research in the field of electronics of heterogeneous structures and materials and can also be used locally.

REFERENCES

1. Починок А. В., Лазурик В. Т., Целуйко Ф. Ф., Боргун Е. В. Компьютерная обработка результатов измерений характеристик плазменного источника ультрафиолета. Вісник Харківського національного університету. Серія фізична «Ядра, частинки, поля», 2008, № 859, с. 59–64.
2. Селиванова З. М., Стасенко К. С. Теоретические основы построения интеллектуальных информационно-измерительных систем допускового контроля теплопроводности теплоизоляционных материалов: монография. Тамбов: Изд-во ФГБОУ ВПО «ТГТУ», 2015, 200 с.
3. Himanen L., Geurts A., Foster A. S., & Rinke P. Data-driven materials science: status, challenges, and perspectives. Advanced Science, 2019, V. 6, No. 21, P. 1900808.1–1900808.23.
4. Климентьев А. А. Методы обработки сверхбольших объемов данных в распределенной гетерогенной компьютерной среде для приложений в области физики высоких энергий и ядерной физики. Физика элементарных частиц и атомного ядра, 2020, Т. 51, Вып. 6, с. 1175–1303.
5. Tonkoshkur A. S., Lozovskyi A. S. Software for processing and analysis of experimental data in researching of gas sensors. System Technologies, 2022, 1(138), P. 175–184. DOI: 10.34185/1562-9945-1-138-2022-17.
6. Кулик І., Тонкошкур О. Додаток для обробки даних діелькометричних вимірювань. Тези доповідей VII Всеукраїнської науково-практичної конференції «Перспективні напрямки сучасної електроніки, інформативних та комп’ютерних систем» (MEICS-2022), Дніпро, 2022, с. 58–59.
7. Gavrikov V. Samovosstanavlivayuschiesya PTC-predohraniteli dlya zaschiti ot tokovih peregruzok. Novosti Elektroniki, 2014, N. 12, P. 11–15.
8. Protecting rechargeable Li-ion and Li-polymer batteries [Electronic resource]: Littelfuse, Inc., 2017. Mode access: http://www.littelfuse.com/....
9. Tonkoshkur A. et al. Application of polymer posistor nanocomposites in systems for protecting photovoltaic components of solar arrays from electrical overloads. International Science Group, 2021.

10. Antonova K. V., Kolbunov V. R., Tonkoshkur A. S. Structure and properties of polymer composites based on vanadium dioxide. Journal of Polymer Research, 2014, V. 21, No. 5, P. 1–5.

11. Kolbunov V. R., Tonkoshkur A. S., Gomilko I. V. Electrical and dielectric properties of polymer composite based on vanadium dioxide. Journal of Materials Science: Materials in Electronics, 2017, T. 28, P. 8322–8328.

12. Morozov I. A., Svistkov A. L., Heinrich G. B. Structure of the carbon-black-particles framework in filled elastomer materials. Polym. Sci. Ser. A, 2007, 49, P. 292. DOI: 10.1134/S0965545X07030091.

13. Montazeri A., Naghdabadi R. Investigation of the interphase effects on the mechanical behavior of carbon nanotube polymer composites by multiscale modeling. J. Appl. Polym. Sci., 2010, 117, P. 361. DOI: 10.1002/app.31460.

14. Tonkoshkur A. S., Lyashkov A. Y., Degtyaryov A. V. Size effects in electrical properties of carbon-polypropylene composites. Ukrainian Journal of Physics, 2016, T. 61, No. 11, C. 1008–1008.

15. Духин С. С., Шилов В. Н. Диэлектрические явления и двойной слой в дисперсных системах и полиэлектролитах. Київ: Наукова думка, 1972, 226 с.

16. Фистуль В. И. Перколяция тока в полимеро-полупроводниковой структуре. Физика и техника полупроводников, 1993, Т. 27, Вып. 11/12, С. 1788–1794.

17. Degtyar'ov A. V., Tonkoshkur A. S., Lyashkov A. Y. Electrical Properties of Posistor Composite Materials Based on Polyethylene-Graphite. Multidiscipline Modeling in Materials and Structures, 2006, V. 2, No. 4, P. 435–441.

18. Bänhegyi G. Numerical analysis of complex dielectric mixture formulae. Colloid & Polymer Science, 1988, V. 266, P. 11–28.

19. Гречко Л.Г. Эффективная диэлектрическая проницаемость матричных дисперсных систем со сферическими металлическими включениями. Поверхня. 2009. Вип. 1. С. 266-270

20. Тонкошкур О. С., Ігнаткін В. У. Фізичні основи електричного контролю неоднорідних систем. Навчальний посібник з грифом МОН. Дніпродзержинськ: ДДТУ, 2010. 290 с.

21. Degtyarlov A. V., Tonkoshkur A. S., Lyashkov A. Yu. Electrical Properties of Posistor Composite Materials Based on Polyethylene-Graphite. Multidiscipline Modeling in Materials and Structures, VSP, 2006, V. 2, No. 4, P. 435–441.

22. Харитонов Е. В. Диэлектрические материалы с неоднородной структурой. Москва: Радио и связь, 1983. 128 с.

23. Shklovskii B. I., Efros A. L. Electronic Properties of Doped Semiconductors. Springer-Verlag, Berlin, 1983.

24. Aneli J., Zaikov G., Mukbaniani O. Physical Principles of the Conductivity of Electrical Conducting Polymer Composites.

25. Shin S.-G., Kwon I.-K. Effect of Temperature on the Dielectric Properties of Carbon Black-Filled Polyethylene Matrix Composites Below the Percolation Threshold. Electronic Materials Letters, 2011, Vol. 7, No. 3, P. 249–254.

26. Kolbunov V. R., Tonkoshkur A. S., Gomilko I. V. Electrical and Dielectric Properties of Polymer Composite Based on Vanadium Dioxide. Journal of Materials Science: Materials in Electronics, 2017, 28, P. 8322–8328.

27. Колбунов В. Р., Тонкошкур А. С., Антонова Є. В., Вашерук А. В. Диэлектрическая спектроскопия композитов на основе полипропилена и диоксида ванадия в радиочастотном диапазоне. Нові технології. Науковий вісник Кременчуцького ун-ту економіки, інформаційних технологій і управління, 2014, № 3-4 (45-46), С. 21–28.

28. Шуп Е. Т. Решение инженерных задач на ЭВМ. Москва: Мир, 1982. 230с.

29. Макаров Е. Г. Инженерные расчеты в Mathcad 15. Москва, 2011. 400 с. https://ru.djvu.online/file/Qei0sgnsq4irc.

30. Программирование в Windows Forms: [Електронний ресурс]. Режим доступу: https://metanit.com/sharp/windowsforms.

31. Use Visual C# to do basic file I/O. Microsoft Learn. [Електронний ресурс]. Режим доступу: https://learn.microsoft.com/en-us/troubleshoot/ developer/visualstudio/csharp/language-compilers/file-io-operation

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Додаток для обробки та аналізу даних вимірювань концентраційної залежності діелектричної проникності двокомпонентних композитів

У статті розглядається розробка та впровадження обчислювального застосунку, призначеного для обробки та аналізу даних, отриманих з діелектричних досліджень. Ці дослідження зосереджені на загальному аналізі типу структури двокомпонентних композитних матеріалів та гетерогенних діелектриків. Запропонований алгоритм використовує експериментальні концентраційні залежності статичної діелектричної проникності для класифікації структури композитів як матричних систем або статистичних сумішей на основі встановлених теоретичних моделей.

Використовуються модель Бругемана-Ханаї для матричних систем та модель Ботчера-Хсу для статистичних сумішей для оцінки діелектричної поведінки гетерогенних систем, що містять провідникові включення. Шляхом апроксимації експериментальних даних за допомогою цих моделей інструмент визначає ключові параметри, такі як фактори деполяризації або порогові значення перколяції, які є критичними для розуміння властивостей таких матеріалів.

Розроблено з використанням Mathcad для алгоритмічної реалізації та Visual Studio – для проєктування інтерфейсу, програмне забезпечення обробляє експериментальні дані з вхідних файлів (формати Excel або текстові файли) та генерує результати у зручному для користувача форматі. Основні функціональні можливості включають перевірку введених даних, обчислення параметрів моделі та візуалізацію результатів. Цей підхід значно підвищує ефективність і точність діелектричного аналізу порівняно з ручними обчисленнями.

Розроблений застосунок має автономні можливості та потенціал для інтеграції в автоматизовані науково-дослідницькі системи для електроніки та науки про матеріали. Це дозволяє дослідникам спрощувати складні математичні обчислення, одночасно забезпечуючи надійний вибір моделей на основі мінімальних помилок апроксимації.

Ключові слова: автоматизація діелектричних досліджень, обробка даних, гетерогенні діелектрики, додаток, Mathcad програма, дизайн інтерфейсу.

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