Implementation of new methods for non-destructing testing of diffusion coefficient in porous material products

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Abstract. New methods for non-destructive testing of diffusion coefficient in thin-sheet and massive products made of isotropic and anisotropic porous materials are considered. In contrast to the rigid structure in the known methods, the represented methods are more flexible in implementing measurement procedures due to higher accuracy of measuring the desired coefficient. Flexibility is provided by calculating experimental data in the preferred sections and by choosing there the static characteristic of the transducer with a stable and noise-proof output signal and in the ranges with high sensitivity to changes in parameters. Expressions for calculating the desired diffusion coefficient for each test subject and a generalized sequence of measurement procedures are introduced. The modified version of the information and measurement system for implementing the proposed methods is described, and the results of the research are presented.

1. Introduction

The use of non-destructive testing (NDT) methods of mass transfer characteristics in porous material products is hindered by the difficulty of measuring local concentrations of diffusing substances [1]. The measuring equipment used for this purpose requires individual calibration for each porous material and the substance diffusing in it [2]. This significantly reduces the testing performance. Such problems do not arise in heat transfer processes as far as static characteristics of temperature transducers (thermocouples, resistance thermometers, IR sensors, etc.) [3,4] and heat flow (heat meters) [5] are independent in most cases from the properties of test objects. This has greatly contributed to the significant advance development of methods for non-destructive testing of heat transfer characteristics in contrast to similar methods for the study of mass transfer processes. Thus, in research of heat transfer processes, NDT methods based on linear [3], flat [6] pulse actions, flat action in the form of a heated circle [4], etc. successfully compete with each other. In the field of mass transfer research, the achievements are rather modest. Therefore, increasing the NDT methods performance of the diffusion coefficient in porous material products is possible when solving the control point localization problem for the concentration of substances distributed in the solid phase [7] and long-term individual calibration of the sensors used in this case [8].

Non-destructive testing methods developed for various types of porous material products (massive [1,2] or thin-sheet [9,10]) to measure the desired diffusion coefficient without a real static characteristic of the used transducer are known. They are based on fixing the time when the maximum
concentration value is reached after a pulse action of a certain configuration (point [2,10] or linear[1,9]) by a dose of a diffusing substance. This is achieved by using a galvanic transducer (GT) with a monotonic static characteristic [7], which allows fixing the time of the maximum concentration of the diffusing substance at the time of the EMF transducer maximum. This eliminates the need to perform long-term calibration of the transducer for each new porous material or when its porous structure changes. However, time recording methods when the maximum concentration value is reached after the pulse action have significant disadvantages:

1) low accuracy of determining the moment when the maximum EMF is reached, where the time derivative of the transducer signal is close to zero, and there is insufficient sensitivity of the measured parameter to time changes;

2) impossibility to fix the moment of maximum concentration in a significant number of cases since this value may fall into the non-working ranges of the GT static characteristic in the area of low concentrations with unstable GT signal due to the high internal electrical resistance of the controlled porous medium or in the area of high concentrations with extremely low sensitivity of the transducer (the limiting case is the area of the diffuser free state in the absence of a connection with the porous skeleton where sensitivity is absent). Therefore, significant time is required for experimental selection of introduced pulse doses of solvent for each new test material and new diffusant, providing the required level for the output characteristic of galvanic transducer.

Thus, the rigid structure of the used methods makes it difficult to apply them for rapid control of the desired parameter in products and does not provide the required accuracy.

2. Problem statement

The goal is to develop new methods for non-destructing testing of the diffusion coefficient in porous material products of various shapes, including those with significant anisotropy signs of mass transfer properties, being flexible to implement measurement procedures and providing increased accuracy and efficiency of control. To achieve the goal, the following tasks are solved:

– to analyze the previously presented methods for their improvement;

– to eliminate additional preliminary studies on the construction of static characteristics of the galvanic transducer for each new porous material and the substance diffusing in it, and thereby significantly increase the efficiency of control;

– to develop the mathematical foundations of new methods and obtain new computational expressions for the diffusion coefficient in thin-sheet and massive porous material products, both isotropic and anisotropic;

– to provide flexibility of measurement procedures, allowing the information and measurement system (IMS) to choose the desired diffusion coefficient segments of curves corresponding to the range with a stable and noise-proof signal of the used transducer, and to use time points at which there are intense changes in its EMF;

– to develop the functioning algorithm and IMS software and conduct its application.

3. Theoretical basis

**Method 1.** Let us consider the basics of the non-destructive testing method of diffusion coefficient in products of sufficient thickness with anisotropy of properties. We will use the ideology, physical model, restrictions on the thickness and size of flat sections of a massive porous material product, as well as restrictions on the size of the pulse line with a solvent dose, the duration of the pulse action and the distance from the GT electrodes to the pulse line, presented in [1] when considering the method with a rigid structure. According to [1], a short-term pulse is applied with a dose of a diffusant along the line located in the middle of a flat section of the product made of a porous material. After that, the surface of the product in the area adjacent to the source is moisture-insulated. These measures allow us to organize the process of spreading the diffusant in a product corresponding to mass transfer in an unlimited body with an instantaneously acting evenly distributed along a straight line source of substance mass. In this case, the change in concentration $U$ is described by the equation [1,11]:

$$U(r, \tau) = W [4\pi D_0 \tau \exp \left( \frac{-r^2}{4Dt} \right)]$$

(1)
where $D$ is the diffusion coefficient; $r$ is the spatial coordinate; $W$ is the power of the instantaneous source of the diffusant dose (evenly distributed amount of the diffusant per unit length of the pulse line); $\rho_0$ is the density of the absolutely dry material under study; $\tau$ is the time; $\delta$ is Dirac delta function.

Here and further, without limiting generality, we assume that the initial content of the diffusant $U_0$ in the material at the initial time is zero.

After the pulse action at fixed distances from the linear source, the concentration of the diffusant changes over time in the form of curves with a maximum at the point $\tau_{\text{max}}$ [1].

The values $D$, coordinates $r_0$, and time point $\tau_{\text{max}}$ under the accepted restrictions are related by the ratio [1,11]:

\[
D = \frac{r_0^2}{4\tau_{\text{max}}}.
\]  

Let us substitute in the expression (1) for an arbitrarily selected coordinate $r_0$ the values of the time moments $\tau_1$ and $\tau_2$, located before and after the moment of time $\tau_{\text{max}}$, corresponding to two arbitrarily selected identical values of concentration. The ration transformation of the obtained expressions taking into account (2) leads to the calculated expression for determining the desired diffusion coefficient:

\[
D = \frac{r_0^2 (\tau_2 - \tau_1)}{4\tau_2 \tau_1 \ln(\frac{\tau_2}{\tau_1})}.
\]  

Thus, the calculated ratio (3) allows us to determine the desired diffusion coefficient by two values of time corresponding to any equal values of concentration on the curves of its growth and loss at the distance $r_0$ from the GT electrodes to the pulse action line. To accelerate the desired diffusion coefficient definition we need to eliminate a time-consuming GT calibration operation. Time registration $\tau_1$ and $\tau_2$ can occur at any equal values of the transducer EMF, and that is provided by the monotony of its output characteristics relative to the concentration diffusant.

**Method 2.** By analogy, let us consider the basics of the method of non-destructing testing for diffusion coefficient in isotropic products of sufficient thickness. We will use the ideology of the method with a rigid structure presented in [2]. The physical model, restrictions on the thickness and size of the flat sections of the porous materials product, as well as restrictions on the size of the pulse application spot by the solvent dose, duration of the pulse action and the distance from the GT electrodes to the pulse application point are the same [2]. According to [2], a short-term pulse is applied by a dose of a diffusant to a point in the middle of a flat section of a massive porous material product with a uniform initial distribution of the diffusing substance. After that, the surface of the product in the area adjacent to the source is moisture-insulated. These measures allow organizing the process of spreading the diffusant in the product corresponding to the mass transfer as a result of an instantaneous substance mass source action at the point of an unlimited body. In this case, the change in concentration is similar to that shown in method 1, and is described by the equation [2,11]:

\[
U(r, \tau) = Q \left(8\rho_0 (\pi D\tau)^{3/2} \exp\left[r^2 / 4D\tau\right]\right),
\]  

where $Q$ is the power of the instantaneous source of the diffusant dose.

After the pulse action with a diffusant dose at a given distance $r_0$ from the point source, a similar change in concentration is observed. The values $D$, coordinates $r_0$, and time $\tau_{\text{max}}$ under the accepted restrictions are related by the ratio [2,11]:

\[
D = \frac{r_0^2}{6\tau_{\text{max}}}.
\]  

After actions similar to those described in method 1, from (4), taking into account the relationship (5), it is possible to obtain a calculated expression to determine the diffusion coefficient:
The calculated ratio (6) allows us to determine the desired diffusion coefficient by the value of the distance $r_0$ from the GT electrodes to the point of the pulse action and by two values of time points corresponding to any equal EMF values of the galvanic transducer in the sections of the EMF growth and loss curve over time.

Method 3. This method is devoted to the study of anisotropic thin material products. We will use the ideology, physical model, restrictions on the thickness and size of flat sections of a thin-sheet material product, as well as restrictions on the size of the pulse line with a solvent dose, the duration of the pulse action and the distance from the GT electrodes to the pulse line, presented in [9] when considering the method with a rigid structure. According to [9], a short-term pulse is applied by a dose of a diffusant along the line in the middle of a flat section of the product placed on an impermeable substrate. The diffusion process in the product is organized in such a way that it is similar in terms of mathematical description to mass transfer in an unlimited medium under the action of an instantaneous flat mass source. To do this, the surface of the product in the area adjacent to the source is moisture-insulated. In this case, the change in concentration is similar to that shown in method 1, and is described by the equation [9,11]:

$$U(x, \tau) = P \left[ P_0 \sqrt{4 \pi D \tau} \exp \left( \frac{x^2}{4D\tau} \right) \right],$$  \hspace{1cm} (7)

where $P_0$ is the power of the instantaneous source of the diffusant dose (the ratio of the linear density of the diffusant distribution to the thickness of the material).

After the pulse action with a diffusant dose at a given distance $x_0$ from the point source, a similar change in concentration is observed. And the values $D$ and $\tau_{\text{max}}$ under the accepted restrictions are related by the ratio [9,11]:

$$D = x_0^2 / (2\tau_{\text{max}}),$$  \hspace{1cm} (8)

After actions similar to those described in method 1, from (7), taking into account the relationship (8), it is practicable to obtain a calculated expression to determine the diffusion coefficient:

$$D = x_0^2 (\tau_2 - \tau_1) \left[ 4 \tau_2 \tau_1 \ln \left( \frac{\tau_2}{\tau_1} \right) \right].$$  \hspace{1cm} (9)

The calculated ratio (9) allows us to determine the desired diffusion coefficient by two values of time corresponding to any equal values of concentration on the curves of its growth and loss at the distance $x_0$ from the GT electrodes to the pulse action line.

Method 4. This method is devoted to the study of isotropic thin material products. We will use the ideology of the method with a rigid structure presented in [10]. According to [10], a short-term pulse is applied to a point in the middle of a flat section of the product with a dose of a diffusant. The diffusion process in the product is organized in such a way that it is similar in terms of mathematical description to mass transfer in an unlimited medium under the action of an instantaneous linear mass source. To do this, the surface of the product in the area adjacent to the source is moisture-insulated. In this case, the change in concentration is similar to that shown in method 1, and is described by the equation [9,11]:

$$U(r, \tau) = M \left[ 4 \pi D r_0 \tau \exp \left( \frac{r^2}{4D\tau} \right) \right],$$  \hspace{1cm} (10)

where $M$ is the power of the instantaneous source of the diffusant dose (the ratio of the introduced amount of the diffusant to the thickness of the thin-sheet porous material).

After the pulse action with a diffusant dose at a given distance $r_0$ from the point source, a similar change in concentration is observed, and the values $D$ and $\tau_{\text{max}}$ under the accepted restrictions are related by the ratio [9,11]:

$$D = x_0^2 (\tau_2 - \tau_1) \left[ 4 \tau_2 \tau_1 \ln \left( \frac{\tau_2}{\tau_1} \right) \right].$$  \hspace{1cm} (9)
After the actions similar to those described in method 1, from (10), taking into account the relationship (11), a calculated expression to determine the diffusion coefficient is obtained:

\[
D = \frac{n_0^2}{(4\tau_{\text{max}})}.
\]  

(11)

The calculated ratio (12) allows us to determine the desired diffusion coefficient by the value of the distance \(r_0\) from the GT electrodes to the point of the pulse action and by two values of time corresponding to any equal EMF values of the galvanic transducer in the sections of the EMF growth and loss curve over time.

Thus, the proposed methods provide significant flexibility and higher accuracy in implementing non-destructive testing of the diffusion coefficient due to the possibility of selecting points on the EMF change curves over time, in contrast to methods with a rigid structure fixing the maximum concentration value. For example, the methods provide the possibility to select the same EMF values from the range in which the transducer signal has the maximum sensitivity and jamming resistance [9,10]:

\[
0.7 - 0.9E_e
\]  

(13)

where \(E_e\) is the signal of the transducer corresponding to the diffusant state not associated with the solid phase of the porous material.

Besides, it is feasible to choose sections of the transducer EMF change curve in time, where the maximum value of a time derivative is observed. It allows reducing essentially the measurement error of time points \(\tau_1\) and \(\tau_2\) and increasing the resultant measurement accuracy of the required diffusion coefficient.

To implement the presented methods, an information and measurement system (IMS) with diffusion coefficient measuring devices for thin and massive material products was used [12]. Devices with point and linear sources are designed to test isotropic and anisotropic porous material products, respectively [12]. The composition of the IMS is similar to that described in [13]. A new algorithmic and software solution is developed to implement the methods presented in this paper.

4. IMS algorithm functioning

To manage the experiment and to process the experimental data, we developed a program in LabView environment from National Instruments [13]. Since measuring devices similar to [12], but with different distances to the sources of the diffusant dose can be used, the possibility to enter arbitrary coordinate values of the galvanic transducer electrodes is provided.

The sequence of measurement operations for the developed methods is shown in table 1.

| Operation № | Operation contents |
|-------------|--------------------|
| 1           | Selection and connection of measuring devices that implement point or linear pulse action on the object under study |
| 2           | Input of the initial parameters required for the operation of the IMS. |
| 3           | Placement of the selected measuring device on the surface of the controlled product. For thin-sheet products, additional insulating substrate is required. |
| 4           | Control of the output characteristic values of galvanic transducers corresponding to the initial distribution of the diffusant in the product. Implementation of short-term contact of the dispenser with a portion of the diffusant at a point or along a line on the surface of the examined material. System startup for conducting the experiment. |
| 5           | Real-time measurement, filtering, and recording of transducer output signals. |
| 6           | Completion of the experiment by operator’s command or when the signal level of the |

5
closest transducer to the source is below the specified level $0.65E_e$.

Selection of the same output characteristic values of the transducer from the range $(0.7 - 0.9)E_e$ on the sections of the curves of their change with a marked increase and decrease in time, if possible, for each of the sensors.

Determination of the values $\tau_1$ and $\tau_2$ for the selected sensors and calculation of the values for the desired diffusion coefficient using the formulas (3), (6), (9), (12).

The IMS software uses the Standard State Machine template [13]. Similar to [13], measurement operations are performed using the tab procedures of the Case structure. When organizing research, the operator from tab 1 selects the type of the examined product in terms of its thickness. Then the operator selects the type of pulse action depending on the preliminary information about the presence or absence of possible anisotropy of the porous material properties. In case of anisotropy, it is necessary to use a linear action. Next, the operator configures the measurement channels and enters the initial parameters.

The experiment starts with a point or linear pulse action of the diffusant on the prepared surface of the control object using the appropriate dispenser. Then tab 2 of the Case structure is used with the "Start" button [13]. On the screen of the graphic indicator, the evolution of EMF transducers located at different distances from the point or line of pulse action application is displayed, in relative units to the maximum signal of the galvanic transducer $E_e$. Signals lower than $0.65E_e$ are ignored because of the increased noise value. At the initial stage of the experiment, some of the sensors close to the source may experience significant oscillations in the output characteristic caused by the unstable mass transfer after the pulse action. In this case, signals that exceed the specified level of oscillation are ignored by the system.

If the signal level of the transducer closest to the source falls below the set level $0.65E_e$, the experiment is automatically terminated or stopped by the "Stop" button. In this case, you will be redirected to tab 3 of the Case structure. This tab contains a subroutine for processing experimental data and calculating the diffusion coefficient. First, the operator sets pairwise values of equal EMF for each of the transducers in the range $(0.7 - 0.9)E_e$ based on visual information about the nature of the evolution curves for the output characteristic of the transducers over time (if possible and appropriate). After that, the search is performed for pairwise values of time points $\tau_1$ and $\tau_2$ for each sensor corresponding to the selected pairwise EMF values. Then the values of the desired coefficient are calculated with the new calculation expressions (3), (6), (9), (12) for each selected sensor. The result of the calculation is displayed on the virtual control panel at the end of the experiment (Figure 1).
5. Experimental results
The developed methods were tested on all types of porous material products, discussed above, using the presented IMS version, adapted to the implementation of methods on two types of measuring devices [12], forming point and linear pulse actions.

The fixed values of the time $\tau_1$ and $\tau_2$, the corresponding values of the moisture diffusion coefficient in an anisotropic building board with oriented fibers, calculated by the formula (4), as well as their deviations from the mathematical expectation are presented as an example in table 2.

### Table 2. Moisture diffusion coefficient in a building board with oriented fibers.

| Experience №, $i$ | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-------------------|----|----|----|----|----|----|----|----|----|----|
| $\tau_{1i}$, s    | 2143.8 | 2358.3 | 2255.4 | 2083.1 | 1709.5 | 2196.6 | 1568.3 | 1742.2 | 2371.8 | 2351.6 |
| $\tau_{2i}$, s    | 4796.4 | 5188.5 | 5186.5 | 4725.6 | 4856.4 | 4901.6 | 4901.6 | 3956.2 | 5362.4 | 3953.4 |
| $D_i \cdot 10^9$, m$^2$/s | 1.28 | 1.17 | 1.2 | 1.31 | 1.6 | 1.25 | 1.73 | 1.57 | 1.15 | 1.33 |
| $\Delta D_i \cdot 10^9$, m$^2$/s | -0.15 | -0.26 | -0.23 | -0.12 | 0.17 | -0.18 | 0.3 | 0.13 | -0.28 | -0.09 |

Here, $\Delta D = (D_i - \overline{D}) \overline{D} = 1.43 \times 10^{-9}$ m$^2$/s is the mathematical expectation of the diffusion coefficient value.

Similar data for the mass transfer of ethyl alcohol in a paper filter with a thickness of 0.22 mm and calculation of the desired coefficient by the formula (13) are shown in table 3.

### Table 3. Ethanol diffusion coefficient in a paper filter.

| Experience №, $i$ | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|-------------------|----|----|----|----|----|----|----|----|----|----|
| $\tau_{1i}$, s    | 1783.2 | 2185.6 | 1555.7 | 1743.6 | 1577.5 | 2181 | 2144.9 | 2106.4 | 1841.6 | 1564.9 |
| $\tau_{2i}$, s    | 4122.8 | 4862.5 | 3862.8 | 4053.9 | 3823.1 | 4723.8 | 4811.7 | 4623.8 | 4236.4 | 3563.8 |
| $D_i \cdot 10^9$, m$^2$/s | 1.52 | 1.26 | 1.69 | 1.55 | 1.68 | 1.28 | 1.28 | 1.31 | 1.47 | 1.74 |
| $\Delta D_i \cdot 10^9$, m$^2$/s | 0.08 | -0.17 | 0.25 | 0.12 | 0.25 | -0.16 | -0.16 | -0.12 | 0.04 | 0.31 |
Experience №, i

| τ₁, s | τ₂, s | Dᵢ · 10⁹, m²/s | ∆Dᵢ · 10⁹, m²/s |
|-------|-------|-----------------|-----------------|
| 1     | 2     | 3               | 4               |
| 357.9 | 390.5 | 496.6           | 518.1           |
| 518.1 | 354.3 | 517.3           | 362.8           |
| 362.8 | 384.2 | 411.5           | 434.9           |
| 1208.6| 1167.5| 1511.2          | 1470.2          |
| 950.8 | 1567.8| 1211.4          | 1313.5          |
| 1231.3| 1244.3|                |                 |

Here, \( \overline{D} = 5.78 \times 10^{-9} \text{ m}^2 / \text{s} \) is the mathematical expectation of the diffusion coefficient value.

6. Results discussion

Experimental studies demonstrate that the error of measuring the diffusion coefficient by the described methods in comparison with the known methods [1, 2, 9, 10] decreases from 6-9 to 4-5% when studying isotropic materials on a point pulse source device, and from 8-13 to 5-7% when studying anisotropic materials on a linear source device.

7. Conclusion

The four new methods considered in this paper provide non-destructive testing of the diffusion coefficient in porous material products with sufficient flat area for placing measuring devices with point or linear pulse sources. Point pulse action methods are intended for the study of massive and thin-sheet products in the absence of noticeable anisotropy of the material properties. Such anisotropic material products are studied by methods that implement linear pulse actions. In comparison with the known methods of non-destructive testing, fixing the moments when the maximum EMF of the transducer is reached, the proposed methods have a higher accuracy. This is provided by selecting the EMF values of the transducer from the preferred range of its static characteristics with a stable and noise-proof signal, as well as registering EMF values on the sections of the curve of their change with a pronounced increase and decrease over time. Control of the diffusion coefficient is performed on previously developed measuring devices with an upgraded version of the information and measurement system, their algorithm of operation and software being adapted to implement these new more flexible methods.

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