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Controlled diffusion of medical textile materials filled with nanomagnetic components

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Abstract. The actuality of the research is defined by the need of creation means for wound treating, the insufficient development of methods of the use of the possibilities of modern nanomaterials. The purpose is to substantiate the possibility of creating materials of a given structure to ensure controlled liquid removal using magnetic nanocomponents. The research involved methods of solving the nonlinear diffusion equation, macroexperiments on liquid sorption by materials filled with nanocomponents. The main approaches and boundary conditions for solving nonlinear equations are substantiated. The approximate analytical solution of the diffusion equation clearly highlighted the possibility of finding the basic diffusion coefficient and the inhibition coefficient, which determines the nonlinear nature of the sorption process. Two experiments register the liquid reaching the opposite surface of the healing material and the mass of the accumulated liquid at a certain time. It has been proven that the introduction of magnetic nanocomponents into the structure of medical materials affects the sorption processes. The addition of magnetic nanocomponents at the initial moment reduces the diffusion coefficients. At the same time, the content of such components increases the bacteriostatic properties of the material. The organisation of the sorption process in the conditions of a variable magnetic field significantly affects the sorption process. An increase in the magnetic field strength significantly increases the diffusion coefficient and decreases the braking coefficient. The dependence of the diffusion coefficients on the content of nanocomponents and the strength of the magnetic field is given in the article. These data make it possible to predict the diffusion properties of the material, as well as to determine the process parameters that provide the specified sorption parameters. The practical value is determined by the possibility of creating materials for the treatment of wounds with adjustable intensity of exudate removal

Keywords: fabric; wound; sorption; nanostructure; exudate removal

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Introduction

The relevance of the research is determined by the contradiction between the need to create effective methods for treating wounds, the potential opportunities of nanocomponents in textile materials and the need to determine their real impact. The particular importance can be related to war in Ukraine that cause the introduction of the latest technologies related to humanitarian issues. In particular, this applies to the treatment of wounds. In some cases, wound treatment involves the use of special bandages. One of the main requirements for such means, as noted by D. Arcangeli *et al.* (2023), should be the removal of exudate from purulent wounds. Optimisation of the wound healing process is related to the possibility of regulating the sorption process. Innovative approaches to creating connections with the necessary authorities have grown significantly. The main requirements for medical textiles and the main achievements in this field are given in the study of R. Rathinamoorthy (2023). At the same time Y.-S. Ho *et al.* (2022) substantiated the main directions of further research on the improvement of wound dressings, which are related to bacteriostatic properties and regulated removal of exudate. The main requirements for fibers and materials are aimed at the intrinsic properties of fibers and textile materials, as described by Y. Qin (2023). In a significant number of studies, the provision of most properties of medical textile materials is associated with the introduction of nanotechnology and nanomaterials. S. Tripathi *et al.* (2023) note the emergence of an additional therapeutic effect in medical textile materials using nanocomponents. As sorption processes related to the structure of the material, the use of porous structures may be relevant for such a system, as shown by M. Nasir *et al.* (2023). In the study of M. Riabchykov *et al.* (2021) the possibility of creating materials with specified porosity parameters, which can be used to create materials with specified sorption parameters is showed.

Thus, the following requirements for medical materials, main achievements and unresolved issues can be noted. The main principle of wound treatment with the help of textile medical materials is the removal of exudate. For each wound, it is desirable to ensure the specified efficiency of this process. The removal process is related to diffusion processes in the material. Theoretically, the sorption process is described by nonlinear differential equations, the general methods of which do not exist. Promising nanocomponents in the composition of textile materials can provide a given structure and corresponding sorption parameters. The location of such materials in the magnetic field additionally regulates these processes. Such materials can demonstrate qualitatively new properties, provide favourable regulation of exudate sorption and, accordingly, more effective treatment. It should be determined that the use of magnetic nanocomponents to regulate sorption parameters is a promising but unexplored direction in the field of medical textiles. At the same time, the determination of normalised diffusion rates for such materials in the express mode remains an insufficiently substantiated issue.

The purpose of this work consists in the justification of the creation of materials with specified parameters of exudate sorption based on the use of nanocomponents in magnetic field conditions.

Materials and methods

The first task for conducting research is to justify the methodology for determining sorption parameters.

Sorption characteristics of the material are related to diffusion processes. This process is described by a nonlinear differential equation taking into account the complex dependence of the diffusion coefficient on the liquid content:

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x} D \frac{\partial U}{\partial x}, \tag{1}$$

where U – the liquid content in relative units to full density.

The diffusion coefficient depends on the liquid content:

$$D = D_0(1 + \sigma \cdot U). \tag{2}$$

In such conditions, the diffusion process is determined by two parameters. The static diffusion coefficient D_0 can theoretically be determined by traditional methods. Methods for determining the saturation coefficient σ are generally unknown. The diffusion equation does not have exact analytical solutions. Approximate solutions given, for example, in the article of L. Yan *et al.* (2023) should be developed for an operational approximate solution.

To determine the diffusion coefficients, a modified semi-emeric method was used. Such method was described by S. Arabuli *et al.* (2018). It consists in the use of analytical dependencies compatible with express experiments on liquid absorption. This method requires the use of analytical solution methods, since the main diffusion constants remain unknown in the solution process. The theory of differential equations indicates that two unknown constants require the use of at least two conditions. Considering the fact that the mass growth of the textile material in the sorption process can be found under experimental conditions, at least two such experiments must be conducted.

Determination of diffusion coefficients is not the end of this work itself. In order to regulate the sorption process, nanomagnetic powder consisting of a mixture of ferric and ferric oxides is added to porous textile materials. Such a powder is synthesised as a result of the process described by M. Riabchykov *et al.* (2022).

The structural characteristics of the material obtained with the inclusion of nanocomponents were determined by microscopy methods.

Sorption processes in the material were determined by weighing methods, as a result, the main indicators and diffusion constants were found. Taking into account the real magnetic properties of the obtained material, a hypothesis was made about the influence of the magnetic field on the structure and dimensions of the cavities inside the material, which should undoubtedly affect the sorption indicators. In order to study this process, a porous material containing magnetic nanocomponents was placed inside a ring magnet with the possibility of adjusting the magnetic field tension. Sorption properties were determined for several cases of stress and content of magnetic nanocomponents.

Results and discussion

The first step of this study was the substantiation of express methods for determining diffusion coefficients. The calculation scheme for the passage of liquid through the material is shown in Figure 1.

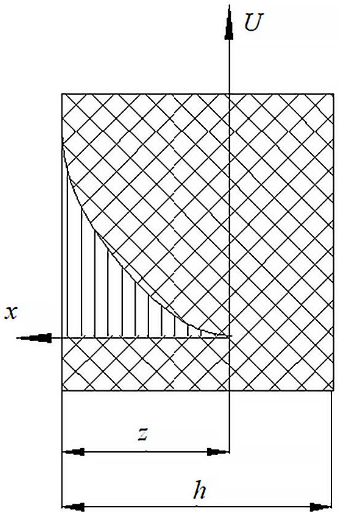

Figure 1. *Calculation scheme of the liquid sorption process*

Source: *developed by the authors on the base of L. Yan et al. (2023)*

A material of thickness *h* is subjected to the action of a liquid from one side. Wetting occurs on the left side of the material. At the same time, complete saturation of the material with liquid is observed at this point, i.e., the saturation value $U = 1$. In a certain time *t*, the liquid reaches a certain point inside the material. In the figure, this distance is denoted by *z*. The differential equation of diffusion in conditions of substituting the diffusion coefficient depending on the liquid content can be converted to the form:

$$\frac{\partial U}{\partial t} = D_0\left(\frac{\partial^2 U}{\partial x^2} + \sigma\left(\frac{\partial U}{\partial x}\right)^2 + \sigma \cdot U \cdot \frac{\partial^2 U}{\partial x^2}\right). \quad (3)$$

The equation has a pronounced non-linear appearance, as it contains terms that include derivatives raised to certain powers. There are no exact methods for solving such equations. To find an approximate equation, was estimated a possible solution taking into account the boundary conditions. For ease of approximation, the origin of the coordinates is located at the point of reaching the liquid. The *x* coordinate from this point was directed to the plane from where wetting occurs.

In this case, the boundary conditions can be written in the form:

$$\begin{aligned} &U=1,\ x=z, \\ &U=0,\ x=0. \end{aligned} \quad (4)$$

A power function meets these conditions. In a simpler form, it can be written as:

$$U = \left(\frac{x}{z}\right)^n. \quad (5)$$

In this expression, it is necessary to determine the exponent of the power function. After substituting into the differential equation, it's possible to can get an equation in which the distance traveled by the liquid is the unknown.

$$\frac{dz}{dt} = -D_0\frac{n}{z}\left[\frac{n-1}{n}\left(\frac{x}{z}\right)^{-2} + \sigma\frac{2n+1}{n}\left(\frac{x}{z}\right)^{n-2}\right]. \quad (6)$$

In the future the dimensionless coordinate will be used for convenience:

$$\vartheta = \frac{z}{h}. \quad (7)$$

Then the equation will be rewritten in the form:

$$\frac{d\vartheta}{dt} = -\frac{D_0}{h}\frac{n}{\vartheta}\left[\frac{n-1}{n}\frac{1}{\vartheta^2} + \sigma\frac{2n+1}{n}\vartheta^{n-2}\right]. \quad (8)$$

It is necessary to take into account fact that the thickness of the material for bandages is small. So, it can be possible to ensure equality at two points, $\vartheta = 0.5$, $\vartheta = 1$. This condition will provide a solution:

$$4\frac{n-1}{n} + \sigma\frac{2n+1}{n}\left(\frac{1}{2}\right)^{n-2} = \frac{n-1}{n} + \sigma\frac{2n+1}{n}. \quad (9)$$

The last equality allows to find the coefficient of nonlinearity depending on the exponent:

$$\sigma = 3\frac{n-1}{2n+2} \cdot \frac{2^{n-2}}{2^{n-2}-1}. \quad (10)$$

At the same time, the distance of liquid diffusion into the material can be determined from the equation:

$$\frac{d\vartheta}{dt} = -\frac{D_0}{h}\frac{n}{\vartheta}\left[\frac{n-1}{n} + \sigma\frac{2n+1}{n}\right]. \quad (11)$$

This equation can be solved exactly. Thus, the dependence of the liquid penetration depth on time can be written in the form:

$$\vartheta = 1 - exp\left\{-\frac{D_0}{h}[n - 1 + \sigma(2n + 1)]t\right\}. \qquad (12)$$

In this equation, the degree and the diffusion coefficient remain unknown. Two results are necessary for the experimental determination of the exponent. The mass of liquid accumulated in the material can be found as an integral:

$$M = A \cdot \rho \int_0^z U(x)dx = A \cdot \rho \int_0^z \left(\frac{x}{z}\right)^n dx = \frac{A \cdot h \cdot \rho \cdot \vartheta}{n+1}. \qquad (13)$$

In this equation, A determines the area of action of the sorption process:

$$\mu = \frac{M}{A \cdot h \cdot \rho}. \qquad (14)$$

When the liquid reaches the opposite boundary, a wetted zone begins to appear on this boundary, which can be fixed. At the same time, the mass of the sample with accumulated liquid can be determined:

$$\mu_0 = \frac{1}{n+1}. \qquad (15)$$

The obtained experimental results allow to determine the degree indicator immediately:

$$n = \frac{1-\mu}{\mu}. \qquad (16)$$

The use of this indicator immediately determines the value of the braking coefficient σ according to the above expression. Integration taking into account the change in the liquid distribution zone determines the mass of the accumulated liquid after a certain time interval.

$$\mu(t) = \frac{1 - exp\left\{-\frac{D_0}{h}[n-1+\sigma(2n+1)]t\right\}}{n+1}. \qquad (17)$$

Weighing the sample over a specified interval allows to determine directly the value of the static diffusion coefficient, taking into account the real spread of the liquid and the presence of the braking process in the process of liquid accumulation. Obvious transformations give an expression for this indicator in the form:

$$D_0 = \frac{h}{[n-1+\sigma(2n+1)]t} ln\big(1 - \mu(t) \cdot (n + 1)\big). \qquad (18)$$

Thus, the process of determining of the diffusion coefficients includes two measurements of the mass of the accumulated liquid. The first measurement determines the mass after a certain period of time while the liquid is inside the material. The second experiment measures the mass of accumulated liquid after wetting the opposite side. This value allows to determine immediately the indicator of the degree of the function of the spread of the liquid during using the dependence shown in Figure 2.

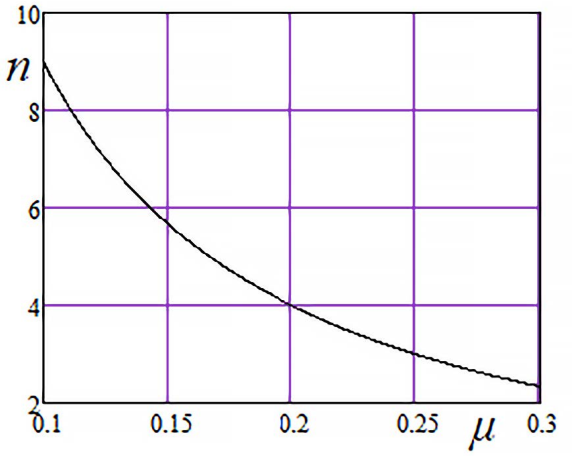

Figure 2. *Indicator of the degree of the distribution function depending on the accumulated liquid*
Source: *developed by the authors*

The inhibition coefficient associated with the nonlinear component of the differential equation determines the influence of the liquid already accumulated in the material on the sorption properties. Considering the above equations, this coefficient can be determined using the dependence shown in Figure 3.

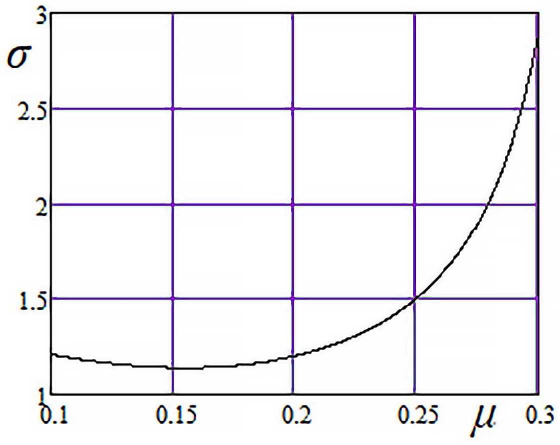

Figure 3. *Braking coefficient depending on the amount of accumulated liquid*
Source: *developed by the authors*

The static diffusion coefficient can be determined based on the liquid accumulated in the material after a certain period of time. At the same time, the dependence will have three factors that must be taken into account. These factors include the total accumulated liquid, the time that must be less than the full soaking time, and the amount of accumulated liquid up to that time. For example, these indicators were determined theoretically for a liquid content of 0.05 from full for different moments of time (Fig. 4).

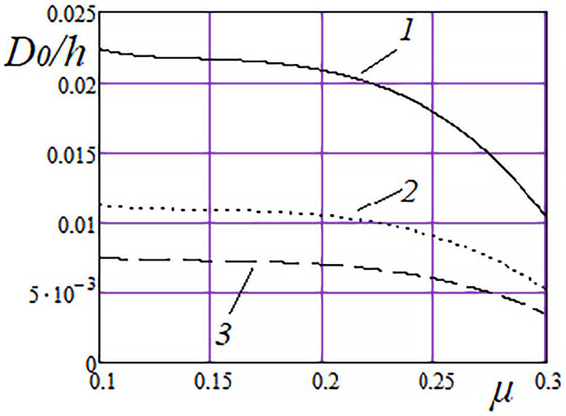

Figure 4. *Static diffusion coefficient for different moments of time*

Note: *1 – t1; 2 – t2; 3 – t3; t1<t2<t3*

Source: *developed by the authors*

Nanomagnetic technologies for filling medical materials fully justify themselves based on their bacteriostatic properties. At the same time, their content in a certain way affects the structure and size of the pores inside such materials. The addition of certain components based on oxides of divalent and trivalent iron in a certain way reduces the average pore size. The study of the microstructure of similar materials, shown in Figure 5, at first glance does not determine a significant impact.

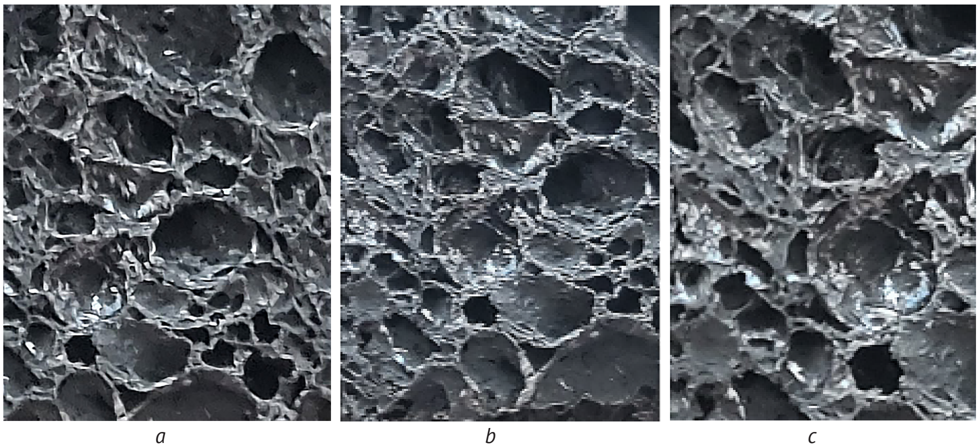

Figure 5. *Structure of porous material saturated with iron oxide nanocomponents, nanocomponent content*

Note: *a – 0.3%; b – 0.2%; c – 0.1%*

Source: *developed by the authors*

A more detailed study of the average size of the structural components shows a decrease in the average pore size by approximately 8-12% with a reduction in size dispersion by the same amount. The decrease in average dimensions determines leads to change in the time of passage of liquid through the textile material. Conducting experimental studies shows a decrease in the static diffusion coefficient and an increase in the braking coefficient. The introduction of magnetic nanocomponents affects the sorption indicators, but does not directly determine the possibility of regulating this process.

In order to regulate the sorption process, the material saturated with magnetic nanocomponents was placed in the area of action of a ring electromagnet with controlled power. The electric voltage, supplied to the electromagnet, was adjusted using an autotransformer. As a result of this process, the strength of the magnetic field changed. On the basis of mechanical gravity tests, the ratio of electric voltage and magnetic field strength was determined. This device allows you to change the strength of the magnetic field in the range from 0 to 3 mT. At different indicators of the content of magnetic nanocomponents and the strength of the magnetic field, samples of the material to be sorbed were weighed. Water was used as a model fluid. According to the method given above, the values of the static diffusion coefficient and the braking coefficient were determined. The results of determining these paraseirs are shown in Figure 6, Figure 7.

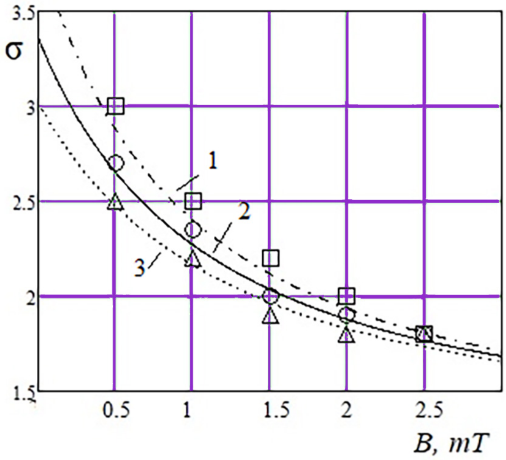

Figure 6. *Change in the braking coefficient depending on the strength of the magnetic field and the content of magnetic nanocomponents*

Note: *1 – 0.1%; 2 – 0.2%; 3 – 0.3%*

Source: *developed by the authors*

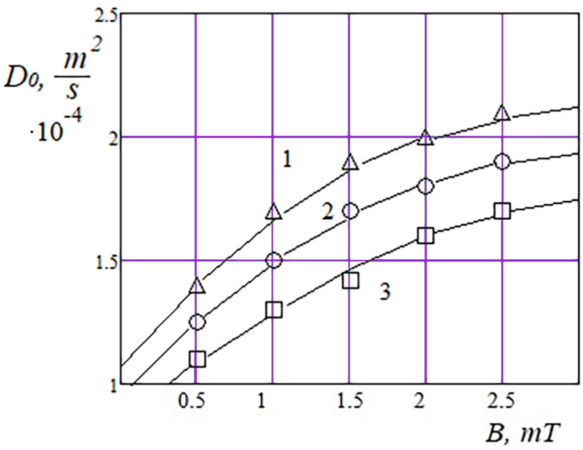

Figure 7. *Change of the static diffusion coefficient depending on the strength of the magnetic field and the content of magnetic nanocomponents*

Note: *1 – 0.1%; 2 – 0.2%; 3 – 0.3%*

Source: *developed by the authors*

The dependences demonstrate a decrease in the diffusion coefficient with an increase in the content of magnetic nanocomponents and an increase in this indicator with an increase in the magnetic field strength. The braking coefficient decreases with an increase in the content of nanocomponents and an increase in the strength of the magnetic field. The obtained results prove the possibility of real regulation of the sorption properties of textile materials in the treatment of wounds. Express methods for determining diffusion indicators have been developed.

In the process of reviewing the main achievements in the field of creation of textile medical materials, additional results obtained in this study were noted. The main requirements for wound dressings determine their effective bacteriostatic and sorption properties. Major advances in the creation of textile materials for wound care are presented in a study of P.D. Venkataraman *et al.* (2023), while the peculiarities of the use of nanotechnologies are noted. A systematic review of the development of wound dressings, as well as the various directions related to their development, are reviewed in a review by Z. Liu *et al.* (2023). In the article of Y. Wu *et al.* (2022) it was considered the main requirements of textile medical materials regarding hygroscopicity, bacterial resistance and certain activity. The results of this research make it possible to significantly expand the nomenclature of medical textiles, taking into account the possibilities of creating a given structure. In a study of N. Zhang *et al.* (2023) the importance of antibacterial properties of medical materials were proved. At the same time, P. Singh *et al.* (2023) claim that the use of nanomagnetic materials significantly increases the bacteriostatic properties of textile materials. Such properties of nanocomponents were additionally proven by R. Masood *et al.* (2015). The main properties of nanocomponents and means of their synthesis are given in the book by H. Gao *et al.* (2023a).

Magnetic nanocomponents, the bacteriostatic properties of which have been proven by previous studies, were used in this study. Thus, the use of such materials is fully justified for medical purposes. G. Chen *et al.* (2023) reported about the technology of saturation of textile materials with nanocomponents for the purpose of protection against bacteria and viruses. In a study by S. Banerjee *et al.* (2023) the facts about the possibility of controlling medicinal liquids in medical textile materials with the addition of nanocomponents are provided.

Regulation of liquid sorption was proclaimed in previous publications, but was not scientifically substantiated. The obtained results confirmed the real possibility of regulating this process. Considering the importance of removing exudate from wounds, a number of publications investigate the process of fluid movement in textile materials. L. Hou *et al.* (2023) determined the gradient of fluid movement through textile materials. M. Riabchykov *et al.* (2022) used mathematical modeling methods to determine patterns of fluid movement through textile materials. S. Stanković (2023) described the parameters of fluid transport through textile materials.

In contrast to known results, the nonlinear nature of the diffusion process and two coefficients characterising the diffusion process are taken into account. The intensity of liquid sorption inside textile materials is related to the definition of the diffusion coefficient, which is not an absolute constant, but is related to the accumulated amount of liquid in the material, as shown in particular by Z. Tan & Y. Zeng (2024). The difficulty of directly determining the values of the diffusion coefficient is noted by X. Linh Nguyen *et al.* (2022). Such researchers as H. Gao *et al.* (2023b) relate sorption characteristics, in particular diffusion coefficients, to porosity parameters. Porosity is generally poorly regulated. In the article of R.K. Prasanth Kumar *et al.* (2024) the possibility of influencing the porosity parameters of the material filled with nanocomponents using a magnetic field was proved. The given partial solutions of the diffusion equations do not have a clear possibility of determining the nonlinear diffusion coefficients. The obtained results will make it possible to determine nonlinear diffusion coefficients based on macro experiments.

A. Mao *et al.* (2022) attempted to model the structure of the textile material to ensure the given sorption properties. Q. Chen *et al.* (2023) investigated the effects of coatings and saturating materials on wet transport performance. Means of controlling fluid movement in textile materials are defined in a study by K. Bal & B. Das (2023). This study clearly shows the prospects of using nanocomposites based on iron oxides to create a certain structure. Y. Lin *et al.* (2023) consider the possibility of controlling fluid movement in a textile material. J. Ma *et al.* (2023) note the possibility of simultaneously ensuring the movement of liquid in a given direction and preserving the bacteriostatic properties of the textile material. It was also noted in the study by M.R. El-Naggar *et al.* (2024) the influence of magnetic nanocomponents on the parameters of diffusion in the material. Additionally, the effect of nanomagnetic particles of iron oxides on sorption processes is considered in the article of C. Wang *et al.* (2024).

This article proves the real possibilities of regulating the movement of liquid in textile materials under the influence of a magnetic field under the conditions of using magnetic nanocomponents.

Conclusions

One of the main indicators of the effectiveness of the functioning of medical textile materials for the treatment of wound infections is the possibility of regulated removal of exudate. The process of liquid sorption by textile materials is strongly non-linear in nature. It is characterised by two diffusion constants that cannot be explicitly determined experimentally. The first indicator determines the static diffusion coefficient, which does not take into account the influence of the amount of saturated liquid on the sorption process. The second indicator demonstrates the process of inhibiting the saturation of the liquid with the textile material. The study provides an approximate solution to the differential equation of diffusion. This solution allows to clearly identify the desired parameters on the basis of express experiments during weighing the sample to be wetted.

The use of nanocomponents based on oxides of divalent and trivalent iron introduced into the structure of the material allows to change the sorption characteristics to a certain extent. In the process of adding nanopowder in the amount of 0.1-0.2%, the diffusion coefficient decreases by 8-12%, correspondingly, the time to remove exudate from the wound increases. Under the influence of a magnetic field, the diffusion parameters of the textile material change. At the same time, the static diffusion coefficient increases from $(0.8\text{-}1.1)\cdot10^{-4}$ m^2/s to $(1.8\text{-}2.2)\cdot10^{-4}$ m^2/s. The braking coefficient decreases from 3.3.5 to 1.7-1.8. The obtained results make it possible really regulation of the process of sorption of textile materials. This fact can significantly improve the effectiveness of treatment of wound infections. Further research involves determining the parameters of materials for real biological fluids and developing practical methods of using the developed technologies.

Conflict of interest

None.

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None.

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Контрольована дифузія медичних текстильних матеріалів, наповнених наномагнітними компонентами

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Анотація. Актуальність дослідження визначається необхідністю створення засобів для лікування ран, недостатньою розробленістю методів використання можливостей сучасних наноматеріалів. Метою роботи є обґрунтування можливості створення матеріалів заданої структури для забезпечення контрольованого видалення рідини з використанням магнітних нанокомпонентів. В роботі використано методи розв'язання нелінійного рівняння дифузії, макрокліматичні експерименти з сорбції рідини матеріалами, наповненими нанокомпонентами. Обґрунтовано основні підходи та граничні умови для розв'язання нелінійних рівнянь. Наближений аналітичний розв'язок рівняння дифузії чітко висвітлив можливість знаходження основного коефіцієнта дифузії та коефіцієнта інгібування, який визначає нелінійний характер сорбційного процесу. У двох експериментах реєструється кількість рідини, що досягає протилежної поверхні лікувального матеріалу, і маса накопиченої рідини в певний момент часу. Доведено, що введення магнітних нанокомпонентів у структуру медичних матеріалів впливає на процеси сорбції. Додавання магнітних нанокомпонентів в початковий момент знижує коефіцієнти дифузії. Водночас вміст таких компонентів підвищує бактеріостатичні властивості матеріалу. Організація процесу сорбції в умовах змінного магнітного поля суттєво впливає на процес сорбції. Збільшення напруженості магнітного поля суттєво збільшує коефіцієнт дифузії та зменшує коефіцієнт гальмування. У статті наведено залежність коефіцієнтів дифузії від вмісту нанокомпонентів та напруженості магнітного поля. Ці дані дають можливість прогнозувати дифузійні властивості матеріалу, а також визначати технологічні параметри процесу, які забезпечують задані параметри сорбції. Практична цінність визначається можливістю створення матеріалів для лікування ран з регульованою інтенсивністю видалення ексудату

Ключові слова: тканина; рана; сорбція; наноструктура; видалення ексудату