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Basic Parameters of Medical Textile Materials for Removal and Retention of Exudate from Wounds
Osnovni parametri medicinskih tekstilij za odvajanje in zadrževanje izcedka pri vnetju ran

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Abstract
The article focuses on predicting the properties of textile materials intended for the treatment of wounds. The main requirements for medical textile materials for liquid transportation were identified. Exudate from wounds and therapeutic fluids from a dressing must move through material with the necessary efficiency. This ensures that unwanted substances are removed from the wound and the necessary moisture is maintained. These requirements can be provided using a mathematical model of the process. Such a model can be substantiated by solving a non-linear differential diffusion equation. For this purpose, the function of changing the moisture content inside a textile material was approximated using a polynomial function that satisfies the boundary conditions. This approximation made it possible to reduce the problem to the solution of an ordinary differential equation with respect to time. The obtained analytical solution of the change in moisture content with respect to time and coordinate includes two diffusion constants. The results of macro-experiments, together with analytical results, made it possible to determine the diffusion coefficient and the nonlinearity coefficient in an explicit form. The results made it possible to predict the moisture content at a given point of textile material at any given time, the total amount of absorbed liquid and the intensity of absorption. The resulting function can recommend the geometric and physical parameters of medical textile materials for the treatment of wounds with a given intensity of exudate sorption.
Keywords: Textile medical materials, diffusion coefficient, nonlinear equation, removal of exudate

Izvleček
Članek se ukvarja z metodo predvidevanja lastnosti tekstilnih materialov za zdravljenje ran. Oblikovane so glavne zahteve za prenos tekočine skozi medicinske tekstilije. Izcedki iz ran in terapevtskih tekočin iz oblog se morajo učinkovito premikati skozi material, da zagotovijo odstranitev neželenih snovi iz rane in ohranitev potrebne vlažnosti. Te zahteve je možno določiti z matematičnim modelom, ki temelji na reševanju nelinearne diferencialne difuzijske enačbe. V ta namen je funkcija spreminjanja vsebnosti vlage v tekstilnem materialu predpostavljena s pomočjo polinoma, ki izpolnjuje robne pogoje. Ta predpostavka je omogočila rešitev problema s pomočjo navadne diferencialne enačbe v odvisnosti od časa. Dobljena analitična rešitev spremembe vsebnosti vlage v odvisnosti od časa usklajuje tudi vključitev dveh difuzijskih konstant. Rezultati makroeksperimentov skupaj z rezultati analize omogočajo določitev koeficienta difuzije in koeficienta nelinearnosti v eksplicitni obliki. Rezultati omogočajo napovedovanje vsebnosti vlage v določeni

točki tekstilije v danem trenutku, skupne količine absorbirane tekočine in intenzivnosti absorpcije. S pomočjo dobljene funkcije se lahko priporoči geometrijske in fizikalne parametre medicinskih tekstilij za zdravljenje ran z dano intenzivnostjo sorpcije izcedka.
Ključne besede: tekstilni medicinski materiali, difuzijski koeficient, nelinearna enačba, odstranitev izcedka

1 Introduction

Military actions in Ukraine have led to a significant increase in the number of wounded people with open wounds. This results in the need for research related to their treatment. Traditionally, there are two main processes in the treatment of gunshot wounds. The first determines the emergency treatment of a wound on the battlefield. This article discusses the conditions for the second stage of treatment in hospitals.

Together with the predominantly medical aspects, this process requires research in technical fields, in particular textiles. Wound dressings remain the primary treatment for wounds [1]. Indeed, in recent years, the design of such bandages has developed significantly, which has increased the effectiveness of their use [2]. It should be noted that such bandages are special textiles. In many cases, they act as active multifunctional devices that remove harmful substances from the wound and deliver medical liquids in the opposite direction. Despite the large number of publications on predicting the kinetics of the passage of liquids through textile materials [3, 4], their results are difficult to use in practice for the design of real textile medical devices.

The main requirements for textile materials for wound healing relate to the need to regulate the movement of fluids removed from a wound on the one hand, and the healing fluids supplied to the wound on the other. In particular, article [5] defines the need for the permanent removal of exudate from purulent wounds [6]. The condition of healing is not merely the removal of exudate. This process must be regulated. It is necessary to maintain the necessary humidity, which can be provided by the parameters of the bandage. Article [7] shows the actual humidity parameters in the area of the bandage when removing exudate. It has been noted that, in some cases, modern bandages do not provide the necessary parameters for the removal of exudate. There is also a need for the subjective control of wound moisture.

It was noted [1] that wound dressings should support the local environment in the wound area. The main process is fluid sorption. These processes can be passive or active.

Research [8] focused on the development of materials that can effectively remove excess exudate from wounds. It was noted that the cavities in such materials should occupy 60–70%. Materials should provide sorption of exudate in the parameters of 1700–1800 g/m^2/day.

Article [9] states that an ideal dressing should effectively remove exudate from wounds. This is a necessary condition for treatment. The structures of nanofiber materials that can provide this process are given.

Study [10] noted the difficulty of measuring the effectiveness of wound dressings in the treatment of complex wounds. Measurements of moisture content and time, as well as treatment processes were determined. The importance of preserving the parameters of the environment at the site of wound healing was noted.

Modern bandages and foams do not always work effectively for wound healing. Article [2] proposes ways to create smart tools that can independently regulate the healing process, in particular the process of removing exudate.

The basic theoretical principles of wound healing consist of several areas [11]. The first determines the creation of the necessary moist environment for the wound. Advances in the creation of special materials have allowed us to focus on creating medical liquids that can help heal wounds. All these processes determine the need for fluid movement through textile medical materials.

Study [12] identified methods for the parameters of the passage of liquids through textile materials, in particular with the help of coloured liquids and real-time moisture content control. The desired structural characteristics to ensure the required parameters of fluid flow were also noted. Article [13] focuses on to the creation of materials that provide the necessary filtering parameters.

Article [14] defines the parameters of the passage of different liquids through fabrics and textiles for different times. The parameters of the moisture content of solutions are also determined.

Nanoparticles of metal oxides improve the performance of medical textiles [15]. These nanoparticles can be located on the surface of such materials [16], or be part of antibacterial liquids that need to be transported with a given efficiency [15].
The creation of effective textile materials, for the treatment of wounds in particular, depends on the presence of a theoretical basis that describes the movement of fluid through the material.
Article [17] focuses on the creation of a mass transfer model through textile materials taking into account various parameters. Study [18] considered comfortable conditions for the use of textiles in terms of heat and liquid distribution.
Processes of filtration of liquid in technical textile materials of water and various mixes are considered in article [19]. Structures for control of filtration process are offered.
The passage of high viscosity liquids through textiles is also described in the study [20].
It should be noted that all theoretical models of medical textiles must use diffusion parameters that in general are not absolute constants. They are determined by the parameters of fluid saturation inside the material.
For these purposes, the values of diffusion coefficients of textile materials are estimated in Article [21]. Hygroscopic experiments are presented. At the same time, the real values of diffusion coefficients raise some doubts. This is especially relevant for the additional accumulation factor.
In study [22], the diffusion coefficient was determined based on the use of the finite element method in conjunction with computed tomography. It is stated that comparisons were made using macro experiments. In general, methods for determining diffusion coefficients are not very developed. It is thus unclear which macro experiments are in question.
Deviations of diffusion parameters from the constant value determine the transformation of differential equations of fluid propagation through textile materials into nonlinear equations. The general means of solving such equations are unknown.
In [23], attempts were made to solve nonlinear diffusion equations using exponential and trigonometric series. Study [24] presents numerical methods of finite differences, and study [25] proposes iterative methods.
Analysis of research proves the relevance of determining the parameters of the passage of fluid through medical textiles. The proposed models of the passage of fluid through such materials are not general in nature and are very difficult to use in practice. Existing methods for determining diffusion coefficients are very complex and do not guarantee real results.
The purpose of this study was to develop practical methods for determining the parameters of the passage of liquid through textile materials for medical purposes, while ensuring the determination of diffusion coefficients based on macro experiments for these materials.

2 Methodology

The essence of the accumulation of fluid in the middle of medical materials is its moisture content in the system of cavities of such materials. Such materials can be a textile weave of threads, or a system of pores for foamed materials. Methods for adjusting the pore parameters for such materials are shown in [26]. The structure of materials with pores for fluid retention is shown in Figure 1.

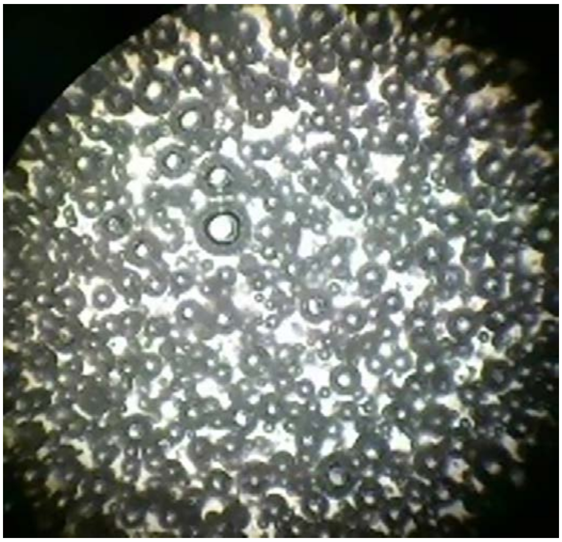

Figure 1: Porous material for medical purposes

The proposed methodology involves the use of generalized material characteristics that are used in the treatment of wounds. Such characteristics allow the data to be averaged and the methods to be applied to various structures such as textiles, foams, and nonwovens.
There are several approaches to determining the parameters of the passage of fluid through medical textiles. The first involves considering the material

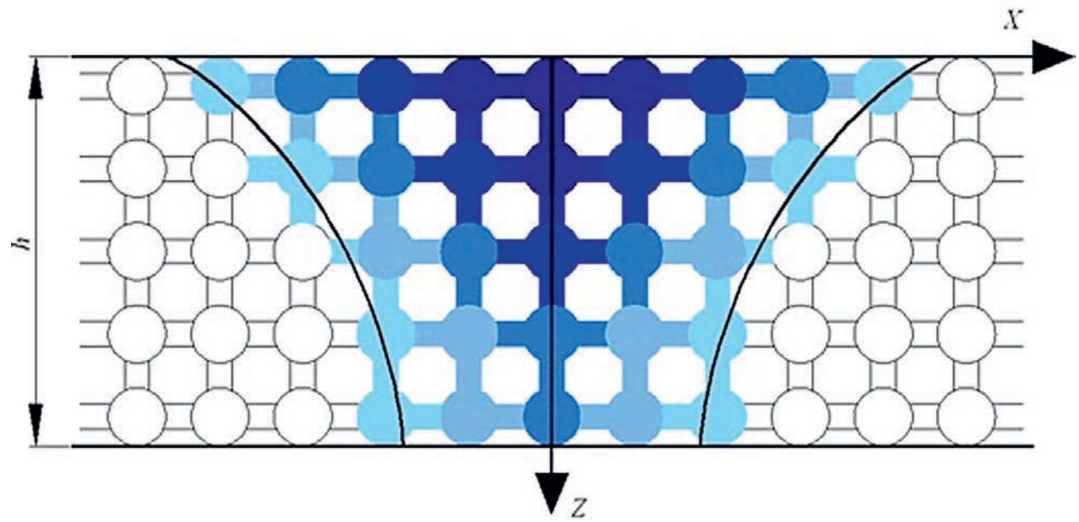

Figure 2: Discrete model of fluid passage through material

in the discrete environment model [4]. Such methods are able to solve complex spatial problems. For example, Figure 2 shows the fluid moisture content profile based on the solution of a discrete problem. As already determined, each individual task requires very large resources and is not suitable for practical use. At the same time, its solution leads to the conclusion that the dependence for fluid moisture content can be approximated using a fairly simple dependence.

Figure 2 shows an X coordinate, which is directed along the surface of the material from the point of penetration of the liquid, a Z coordinate, which is directed from the surface of penetration of the liquid deep into the material, and h indicating material thickness.

Despite the fact that the mechanics of fluid accumulation in the material has a discrete nature, it is more convenient to describe the diffusion process in continuous functions using a differential equation.

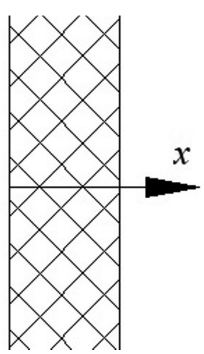

Figure 3: Estimated scheme of fluid movement through material

The passage of liquid through textile materials can be described using the differential diffusion equation. Consider the calculation scheme in the form of a uniaxial model. In this case, the propagation axis is denoted by x, the propagation time t, and the liquid moisture content U at the point.

The differential diffusion equation for such a scheme takes the form [3]

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial U}{\partial x}\right) \tag{1}$$

where ∂ is the partial derivative.

The diffusion coefficient D in most sources is considered to depend on the liquid moisture content. In particular, the dependence in the form is proposed in [4] $D = D_0(1 + \sigma \cdot U)$, where σ - is the coefficient of influence.

In this case, the differential diffusion equation will be rewritten as

$$\frac{\partial U}{\partial t} = D_0\sigma\left(\frac{\partial U}{\partial x}\right)^2 + D_0\frac{\partial^2 U}{\partial x^2} + D_0\sigma U\frac{\partial^2 U}{\partial x^2} \tag{2}$$

The following facts should be noted for this equation

The equation is nonlinear, while the general methods for solving such equations are unknown. The coefficients characterizing the diffusion properties of a textile material are generally quite difficult to determine. You can use additional experiments to determine them, which then require the use of solutions of the equation. This means the desirability of analytically solving the diffusion equation. It should be noted that the numerical solutions [24, 25] are insufficient because they require the numerical values of the coefficients.

At the same time, attempts to determine diffusion coefficients on the basis of numerical modelling of the structure of textile material [23] require a very large amount of preparatory work separately for each material.

It would be desirable to develop approximate analytical methods for solving the diffusion equation, which can simultaneously help determine the diffusion coefficients and control the parameters of fluid flow through textile materials.

Let's move on to dimensionless coordinates: dimensionless moisture content $u = \frac{U}{U_0}$, where U_0 is determined by the liquid coming from the outside to the material (the moisture content of the liquid at zero moment of the absorption process); dimensionless coordinate $z = \frac{x}{h}$, where h is the thickness of the material; dimensionless time $\tau = \frac{t}{t_{\max}}$, where t_{max} is the saturation time of the material.

Then functions and derivatives can be written as:

$$U = u \cdot U_0; \qquad \frac{\partial U}{\partial t} = t_{\max} U_0 \frac{\partial u}{\partial t};$$

$$\frac{\partial U}{\partial x} = \frac{U_0}{h}\frac{\partial u}{\partial z}; \qquad \frac{\partial U^2}{\partial x^2} = \frac{U_0}{h^2}\frac{\partial^2 u}{\partial z^2}.$$

In view of the above, equation (2) should be rewritten as:

$$\frac{\partial u}{\partial \tau} = \frac{D_0 \sigma U_0}{t_{\max} h^2}\left(\frac{\partial u}{\partial z}\right)^2 + \frac{D_0}{t_{\max} h^2}\frac{\partial^2 u}{\partial z^2} + \frac{D_0 \sigma U_0}{t_{\max} h^2} u \frac{\partial^2 u}{\partial z^2} \qquad (3)$$

Let's introduce additional definitions:

$$K_1 = \frac{D_0}{t_{\max} h^2}; \qquad K_2 = \frac{D_0 \sigma U_0}{t_{\max} h^2}$$

The equation can be obtained in the form:

$$\frac{\partial u}{\partial \tau} = K_1 \frac{\partial^2 u}{\partial z^2} + K_2 u \frac{\partial^2 u}{\partial z^2} + K_2 \left(\frac{\partial u}{\partial z}\right)^2 \qquad (4)$$

Note that the diffusion coefficients in the equation are still unknown. Therefore, it is desirable to solve the equation analytically. Given the small thicknesses of the materials under consideration, we will solve the equation for the centre point. Given the results of discrete modelling, a change in fluid moisture content in the thickness of the material will be determined as a power function of the second order $u = w_0 - w_1 \cdot z + w_2 \cdot z^2$, where the coefficients can be time-dependent only.

To analyse the parameters of the passage of liquids through textile medical materials, an experiment, shown in Figure 4 was also built.

Liquid was fed to the surface of material 1, from dispenser 2. A sample of the material was located on mobile device 4. The presence and moisture content of liquid on the upper and lower surfaces was monitored by determining the brightness of the two cameras 4 and 5.

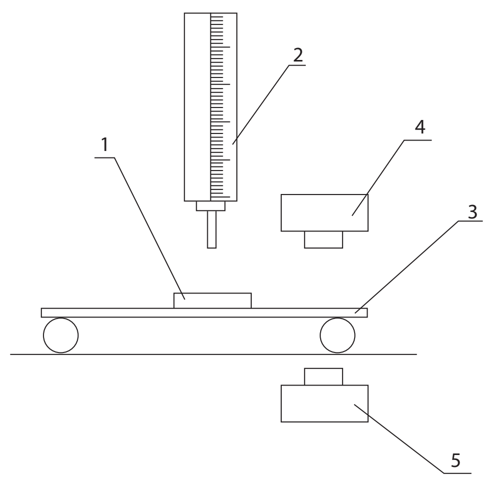

Figure 4: Research device

The parameters of the sample under study are shown in Figure 5.

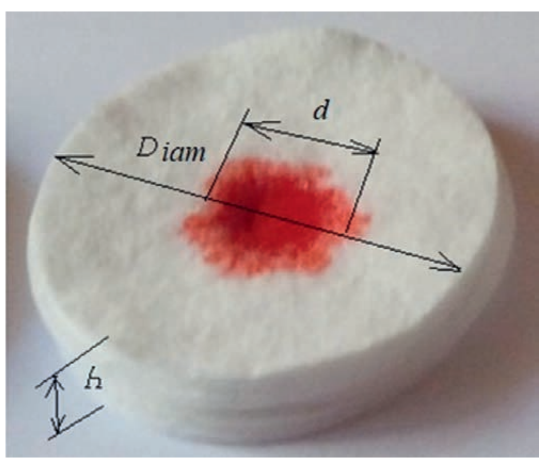

Figure 5: Prototype

The experimental technique facilitates the determination of the time of appearance of liquid on the lower surface of the material, as well as the intensity of the brightness to determine the moisture content of liquid on the upper and lower surface of the material.

3 Results and discussion

When searching for a solution to the equation, the initial and boundary conditions must be taken into account. For the zero-coordinate $x = 0$, the dimensionless moisture content on the surface at any time is equal to one. For the opposite boundary, the moisture content derivative in the coordinate is zero.
Given the relatively small thickness of the textile material, the dependence of a change in moisture content on the thickness in the form of a polynomial of the second order is proposed.

$$u = w_0 - w_1 \cdot z + w_2 \cdot z^2$$

Given the first boundary condition, it is possible to rewrite

$$u = 1 - w_1 \cdot z + w_2 \cdot z^2$$

In the following we will consider two stages of liquid passage through material. The first stage involves the moisture content of liquid inside the material without going outside.
Let us denote the coordinate of the point s to which the liquid inside the material has reached.
Then the equation for this stage will be rewritten in the form

$$u = 1 - 2 \cdot \frac{z}{s} + \frac{z^2}{s^2}.$$

in the centre of the layer at $z=s/2$ moisture content

$$uc = \frac{1}{4}$$

For this central point, the equation can be written as

$$\frac{ds}{dt} = 5 \cdot K_2 \left(\frac{1.2\frac{K_1}{K_2} + s}{s} \right)$$

Once marked $\beta = 1.2\frac{K_1}{K_2}$, the solution can be found in the form

$$s + \ln\left(\frac{\beta}{\beta + s}\right)^{\beta} = 5K_2 \cdot t$$

Given the real values of the parameter β, it is possible to write approximately

$$s \approx 5K_2 \cdot t$$

The moisture content inside the material can be written as dependence

$$u = \begin{cases} 1 - 2 \cdot \dfrac{z}{5K_2 \cdot t} + \dfrac{z^2}{(5K_2 \cdot t)^2}, z < 5K_2 \cdot t \\ 0, z > 5K_2 \cdot t \end{cases}.$$

The time the liquid reaches the opposite surface is

$$t_0 = \frac{1}{5K_2}$$

This dependence implies the possibility of determining at least one of the two diffusion constants, since the time of appearance of the liquid can be recorded, for example, according to the scheme of Figure 2.
The second stage of fluid distribution determines the appearance of fluid on the outer surface.
Taking into account the second boundary condition transforms the dependence for moisture content in the form

$$u = 1 - w_1 \cdot z + \frac{w_1}{2} \cdot z^2$$

In the centre of the layer at z=1/2

$$uc = 1 - w_1 \cdot z + \frac{w_1}{2} \cdot z^2 = 1 - \frac{3}{8} w_1$$

For the central point of the diffusion, the equation can be rewritten as

$$\frac{dw_1}{dt} = -\frac{2}{3} K_2 \cdot \left[4 \cdot w_1 \left(1 + \frac{K_1}{K_2}\right) - \frac{5}{3} w_1^2 \right]$$

Denoting $\alpha = \frac{12}{5}\left(\frac{\sigma \cdot U_0 + 1}{\sigma \cdot U_0}\right)$, we can find the solution of this equation in the form $\frac{1}{\alpha} \ln \frac{C \cdot w_1}{\alpha - w_1} = -\frac{10}{9} K_2 \cdot t$, where C is the integration constant.

This equation facilitates the explicit expression of unknown function

$$w_1 = \frac{\alpha \cdot \exp\left(-\frac{10\cdot\alpha}{9}K_2\cdot t\right)}{C+\exp\left(-\frac{10\cdot\alpha}{9}K_2\cdot t\right)}$$

It can be rewritten as

$$u = 1 - \frac{\alpha \cdot \exp\left(-\frac{10\cdot\alpha}{9}K_2\cdot t\right)}{C+\exp\left(-\frac{10\cdot\alpha}{9}K_2\cdot t\right)}\left(z-\frac{z^2}{2}\right)$$

An unknown constant can be found from the condition of equality of moisture content at the end of the first stage and the beginning of the first stage.

$$u = 1 - \frac{\alpha \cdot \exp\left(-\frac{10\cdot\alpha}{9}K_2\cdot t\right)}{\frac{1}{2}\alpha\cdot\exp\left(-\frac{2\cdot\alpha}{9}\right)-\exp\left(-\frac{2\cdot\alpha}{9}\right)+\exp\left(-\frac{10\cdot\alpha}{9}K_2\cdot t\right)}\left(z-\frac{z^2}{2}\right)$$

We note two diffusion constants $K2$ and α, which are clearly related to the diffusion coefficients D_0 and σ.

If time is chosen as a constant, one can write for the first stage

$$u = \begin{cases} 1 - 2\cdot\frac{z}{t/t_0} + \frac{z^2}{\left(t/t_0\right)^2}, z < t/t_0 \\ 0, z > t/t_0 \end{cases}.$$

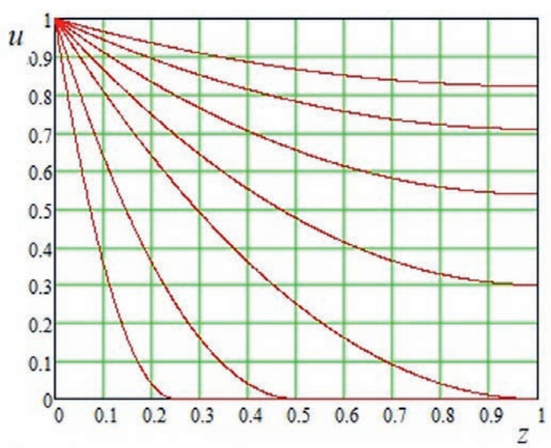

Figure 6: Change in thickness moisture content for different points in time

For the second stage

$$u = 1 - \frac{\alpha \cdot \exp\left(-\frac{2\cdot\alpha}{9}\frac{t}{t_0}\right)}{\frac{1}{2}\alpha\cdot\exp\left(-\frac{2\cdot\alpha}{9}\right)-\exp\left(-\frac{2\cdot\alpha}{9}\right)+\exp\left(-\frac{2\cdot\alpha}{9}\frac{t}{t_0}\right)}\left(z-\frac{z^2}{2}\right)$$

The dependence of a change in moisture content on the thickness of the material for different moments of time is shown in Figure 6.

The total amount of liquid inside the material can be found as an integral of the moisture content (Figure 7).

$$W(t) = \int_0^1 u(z,t)dz$$

The intensity of the increase in moisture content can be found as a derivative (Figure 8).

Moisture content on the outer surface of the material

$$u = 1 - \frac{\alpha \cdot \exp\left(-\frac{2\cdot\alpha}{9}\frac{t}{t_0}\right)}{\alpha\cdot\exp\left(-\frac{2\cdot\alpha}{9}\right)-2\cdot\exp\left(-\frac{2\cdot\alpha}{9}\right)+2\cdot\exp\left(-\frac{2\cdot\alpha}{9}\frac{t}{t_0}\right)}$$

Record the time that is twice the time of passage of the liquid through the material. Then the moisture content at this point on the surface of the material

$$u1 = 1 - \frac{\alpha \cdot \exp\left(-\frac{4\cdot\alpha}{9}\right)}{\alpha\cdot\exp\left(-\frac{2\cdot\alpha}{9}\right)-2\cdot\exp\left(-\frac{2\cdot\alpha}{9}\right)+2\cdot\exp\left(-\frac{4\cdot\alpha}{9}\right)}$$

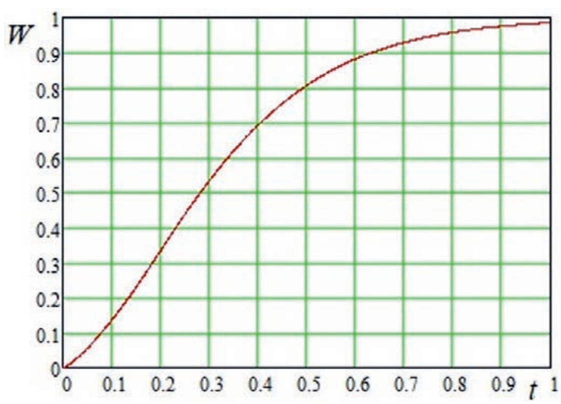

Figure 7: Placement of liquid in material

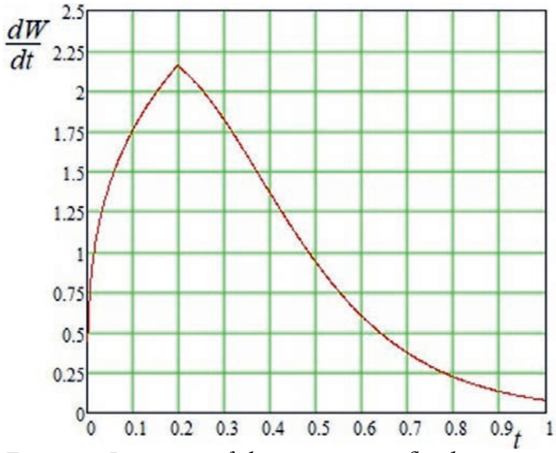

Figure 8: Intensity of the increase in fluid moisture content

Figure 9: Determination of the nonlinearity coefficient

The obtained dependence is approximated using the expression

$$u1 = 1 - e^{-0.26(\alpha - 2)}$$

Where it is possible to find

$$\alpha = 2 - \frac{\ln(1 - u1)}{0.26}$$

Where the nonlinearity coefficient is

$$\sigma \cdot U_0 = \frac{12}{5\alpha - 12} = \frac{12}{19.23 \cdot |\ln(1 - u1)| - 2}$$

Thus, the expressions obtained in the solution, facilitate the determination of the diffusion coefficients for medical material on the basis of macro-experiments.

After that, it is possible to predict the amount and intensity of exudate removal from a wound using medical material of arbitrary size. The resulting function includes both time parameters and penetration depth parameters. It is therefore possible to determine the liquid content at any point along the depth at any time.

Experimental studies of liquid for the material medical cotton wool with a density of 15–17 kg/m^3 (Figure 10) were conducted, which confirmed the performance of the constructed mathematical model.

In further studies, real experimental studies are planned to determine the diffusion coefficients of various materials and the use of the above methods for the design and functioning of real materials.

The difference in the determination of experimental and theoretical data over time is graphically shown in Figure 11. The deviation for a number of experiments varies over time, but the average value of *D* over all time does not exceed 3.4%.

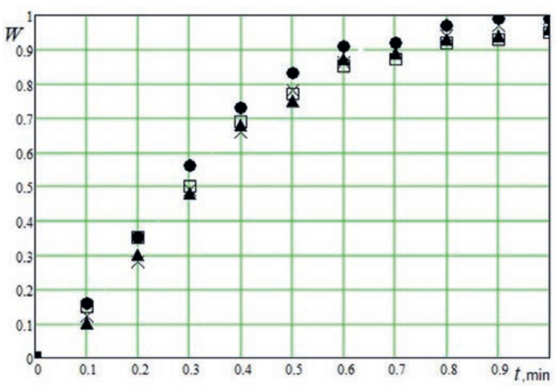

Figure 10: Experimental data of moisture content in medical cotton wool

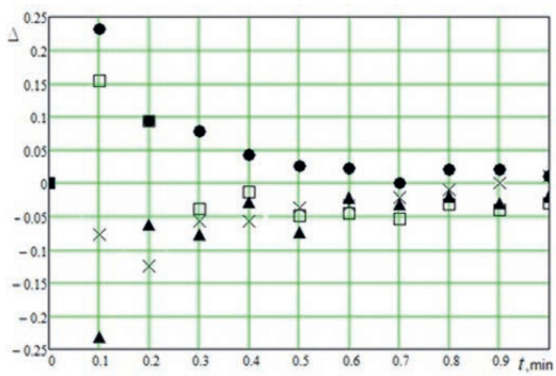

Figure 11: Deviation of experimental data

4 Conclusion

A function that facilitates the determination of the amount of exudate removed from a wound using textile medical materials is obtained on the basis of the approximate analytical solution of the diffusion equation.

These results facilitate the prediction of the condition of a dressing at any time. These mathematical equations take into account the geometric parameters of the bandage. One can predict the process of exudate movement for a dressing of any size or determine the geometric and structural parameters of the material to achieve a given intensity of exudate movement.

The solution is obtained in general form. Indicators of the porosity and hydrophilicity of the substrate, and the density and viscosity of the liquid affect the values of the diffusion coefficients, but not the form of the equation. The solution has been experimentally verified for one type of material (medical cotton wool). Additional studies will focus on the dependences of these coefficients on the characteristics of the material and liquid.

The obtained methods facilitate the determination of the diffusion coefficients and nonlinearity coefficients on the basis of macroexperiments.

These results can have a positive effect on the effectiveness of medical textiles.

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