Досліджені ефекти, що виникають в багатошарових текстильних матеріалах при розповсюджені рідини. Доведена ефективність використання дискретного моделювання, що найліпшим чином відповідає структурі матеріалу. Визначений ефект додаткового змочування, який полягає в розширенні зони змочення на певній відстані від границі матеріалу. Запропоновані регресійні залежності, що описують процес розповсюдження рідини

Ключові слова: текстильні матеріали, розповсюдження рідини, терапевтичні системи, транспортування лікувального матеріалу, бавовна

Исследованы эффекты, возникающие в многослойных текстильных материалах при распространении жидкости. Доказана эффективность использования дискретного моделирования, которое наилучшим образом соответствует структуре материала. Определен эффект дополнительного смачивания, который заключается в расширении зоны смачивания на определенном расстоянии от границы материала. Предложены регрессионные зависимости, описывающие процесс распространения жидкости

Ключевые слова: текстильные материалы, распространение жидкости, терапевтические системы, транспортирование лечебного материала, хлопок

UDC 687.03+62-486+532.685
DOI: 10.15587/1729-4061.2016.85784

DEVELOPMENT AND APPLICATION OF THE DISCRETE MODEL OF MULTI-LAYERED TEXTILE MATERIALS

G. Shchutska
PhD, Associate Professor
Higher state educational establishment "Kyiv college of light industry"
I. Kudri str., 29, Kyiv, Ukraine, 01601
E-mail: polischuka.kklp@gmail.com

1. Introduction

Lately, there has been an increasingly widely spread use of multi-layered textile materials throughout the world. A correct combination of layers allows creating materials with new properties. Their use is in many cases predetermined by hygienic requirements. They can solve the problem of removing metabolic excretions or the problem of supplying useful liquids to the skin. At the same time, it should be recognized that the existing methods for determining characteristics of such materials are not substantiated enough and require more in-depth study.

Multi-layered textile materials find their use in many areas. One of the main areas is medicine where they are used in the form of textile therapeutic systems. In such multi-layered systems, medical material is transported through the layers of material. In this case, medication comes to the skin of a patient by dozes in the assigned sequence. Another example may be removal of metabolic liquids from the surface of the human body.

Methodology of creating such materials is based on intuitive approaches. In some cases, a deviation from the planned characteristics is observed. Certain observations prove the effects of additional accumulation of fluid in one layer of the material. This can lead to improper dosage of a medical liquid. At the same time, taking into consideration such effects will make it possible to regulate its passage properly.

Thus, there is a contradiction between modern humanistic and medical demands for the creation of multi-layered textile materials and disadvantages in identifying effects that appear in them with the passage of fluid. This contradiction makes the research in this direction relevant.

2. Literature analysis and problem statement

An important characteristic of textile materials is their ability to absorb moisture. In some cases [1, 2], these characteristics become the most important. Such cases include the use of materials as protective barriers [3], in which the passage of fluid should be decelerated by means of selecting the properties of separate layers. In addition, they can be used as therapeutic textile means [4].

The problem of moisture distribution in textile materials was the focus of attention of a number of researchers. In [5], a complex multi-level model of textile material is presented. The process of sorption was considered at the level of fibers, threads, and fabrics. In the study of fibers, nonlinear equation of diffusion was used. The fabric was presented in two-dimensional models. Large complexity of the obtained results makes their practical use difficult.

In article [6], a two-staged algorithm of modeling threads as finite elements was developed. A number of papers contain information about using special textile materials, capable of absorbing moisture, in taking care of sick people. Papers [7, 8] are aimed at defining the areas of using such materials; in particular, they contain description of the process of moisture absorption. However, the real models of absorption are not described. The emergence of such models can help in the creation of new materials, as well as predict the properties of existing ones.

To evaluate the properties of fabrics, techniques of different objectivity levels are used [9]. In a number of cases, they allow determining the effect of properties of the material [10], as well as the properties of fiber components, on their form and dimensions [11, 12]. The influence of properties of yarns was explored in [13, 14], properties of fabrics in the process of production – in [15, 16] and finishing treatment – in [17, 18]. The properties of fabric intended for making clothes were identified in order to evaluate their convenience for wearing [19].

Article [20] explores water-resistance of multi-layered fabrics, which consist of simple types of fabric weave (plain, twill) and microporous film with air penetration. In papers [21, 22], authors attempted to create a model of moisture penetration in such materials. The obtained results, however, are difficult to put into practice, due to their complexity.

Article [23] is devoted to substantiation of the discrete model of materials. The results of this article relate mainly to the processes of fluid flowing. It would be desirable to use these results for modeling the processes of fluid accumulation, with regard to the directions of development of three-dimensional textile materials, which has been carried out recently.

In papers [24, 25], discrete methods of modeling moisture passing through the material were proposed. The material is presented in the form of the system of pores and of the bonds between them with the defined discrete characteristics.

The problem of modeling the fluid passage through similar materials is related to the fact that there are some attempts to solve the problem of really discrete textile materials by using continuous methods. These methods have two shortcomings. Firstly, mathematical models of these methods are too overloaded. Secondly, they do not determine the effects of additional absorption of liquids, listed above.

3. The aim and the tasks of the study

The aim of the work is the development and use of the discrete model of multi-layered textile materials for the substantiation of effects of additional distribution of fluids and their further use in creating materials with the required sorption characteristics.

To achieve the set goal, the following tasks were to be solved:

– to carry out a numerical analysis of fluid distribution in an one-layered material based on discrete modeling for testing this procedure;

– to identify the patterns of fluid distribution in multi-layered material;

– to define effects that occur in multi-layered materials;

– to propose regressive dependences for describing the process, to define the necessary constants describing fluid passage through the material.

4. Materials and methods of exploring moisture distribution in textile materials

The study was based on combining continuous and discrete methods for obtaining actual characteristics of the material.

It was proved [23] that textiles, leather and other fractal materials may be considered in discrete models; in this case, the methods of their calculation become considerably simpler. The material, which is exposed to the influence of fluid, in this case is represented in the form of a system of cells and transitions for moisture flowing. At the points of contact of elementary sections, a moisture overflowing occurs, and, depending on the properties of materials, this flowing may take asymmetric form. At the points of contact, a separation of fluid streams occurs. The total distribution of fluid can be considered in relation to the actual structure of discrete material.

Based on the proposed model, an algorithm was constructed [24, 25], which was implemented in the program for the calculation of textile material. An additional advantage of the algorithm is the possibility to determine the geometry of the wetted boundary in the material, which was quite difficult to do in other models. These results can be very useful when designing technological processes of dyeing, cleaning or other processes of chemical treatment. Based on the obtained results, it is possible to predict exact boundaries of wetting, taking into account anisotropy of material, its actual structure, and flowing conditions.

Fig. 1 shows dynamics of change in the wetted zone inside material, based on discrete modeling.

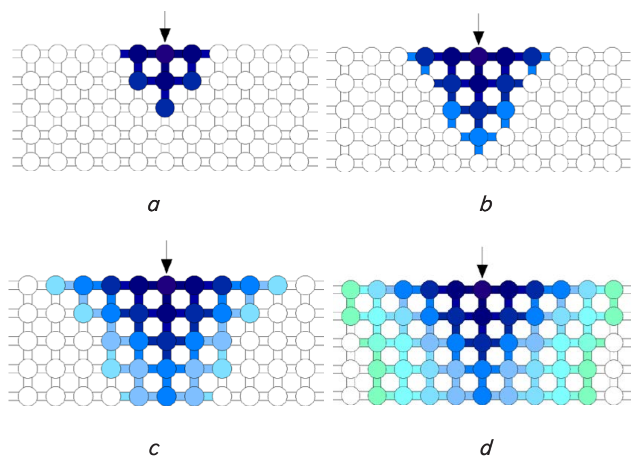

Fig. 1. Dynamics of wetted zone at discrete modeling: *a* – start of sorption process; *b* – reaching inner surface by moisture; *c* – moisture distribution in transverse direction; *d* – complete moisture accumulation in material

We will further consider a scheme of fluid penetration in the form shown in Fig. 2. Coordinate X will be plotted horizontally, it will determine the size of the wetted zone, coordinate Z will be directed from the surface to the depth of material, it varies in the range from zero to the magnitude of material thickness.

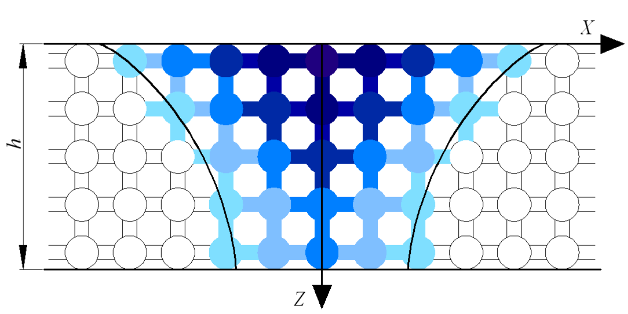

Fig. 2. Conversion of discrete distribution into continual

Fig. 3 demonstrates discrete points of reaching a certain boundary by fluid and the approximating curve for time point t.

Proceeding from a discrete model to the continual, we will select function in the form of exponential dependence.

$$x(z) = a \cdot e^{-bz}. \qquad (1)$$

Here and further on, we will use dimensionless coordinates

$$z = \frac{Z}{h}, \quad x = \frac{X}{X_{max}}, \quad X_{max}$$

is the zone of fluid distribution, maximum by time.

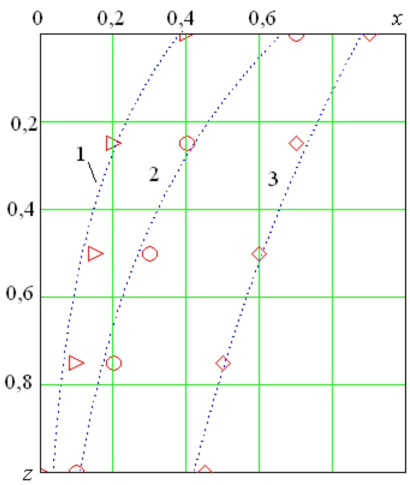

Fig. 3. Dynamics of change in wetted zone: 1 — in ten minutes 2 — in twenty minutes, 3 — in thirty minutes

Using the least squares method, we find equation of regressions for different parameters of time.

Dependence of coefficient b for the case of discrete modeling is shown in Fig. 4.

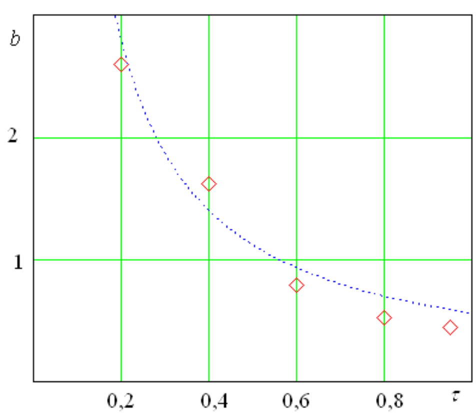

Fig. 4. Dependence of coefficient b on time

Dependence of the coefficient on time will be searched for in the form

$$b = \frac{k_1}{\tau^{k_2}}. \qquad (2)$$

The solution with the help of the least squares method for cotton material yields expression for the coefficient

$$b = \frac{0{,}56}{\tau^{0{,}97}} \approx \frac{0{,}56}{\tau}. \qquad (3)$$

Using similar method, we obtain dependence for coefficient a.

Function of dependence of this coefficient on time, found by the method of discrete analysis, is shown in Fig. 5.

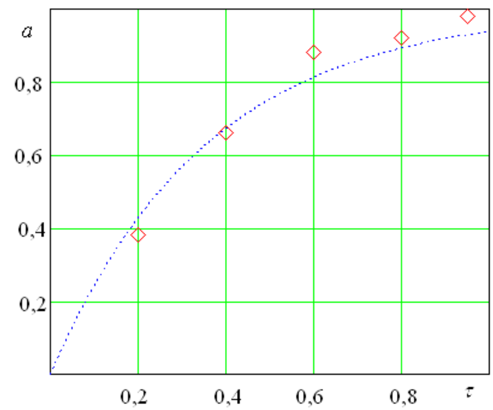

Fig. 5. Dependence of coefficient a on time

We will seek approximating function in the form

$$a = 1 - k_3 \cdot e^{-k4 \cdot \tau}. \qquad (4)$$

As a result, we obtain equation of change in the boundary of wetted zone for cotton fiber in the form

$$x = e^{-0{,}56\frac{z}{\tau}} \cdot \left(1 - e^{-2{,}8\tau}\right). \qquad (5)$$

In an arbitrary case, coefficients of regression may depend on discrete parameters of anisotropy. In this case, a general expression for the boundary of the wetted zone can be determined as

$$x = e^{-A1\frac{z}{\tau}} \cdot \left(1 - e^{-A2\tau}\right), \qquad (6)$$

where A1, A2 are the functions of discrete parameters.

5. Results of modeling fluid distribution in thick multi-layered materials

Based on the obtained results, it is possible to predict the exact boundaries of wetting taking into account anisotropy of the material, its actual structure, and the conditions of flowing.

Results of the studies for determining the sorption characteristics of cotton material with a constraint layer are given below.

Fig. 6 displays dynamics of change in the wetted zone inside the material, based on discrete modeling.

Numerical modeling for the discrete medium revealed the effect of increasing concentration of fluid inside the material, called the paradox of inner concentration. This effect manifests itself in the fact that at certain ratios of discrete parameters of the medium, the maximum fluid distribution occurs not at the surface of the material, but at a certain depth. The emergence of this effect is determined by the parameter that connects geometric properties of the material and the discrete parameters of fluid passage.

The emergence of the effect is determined by the critical value of parameter

$$P = \frac{h}{A} \cdot \left(\frac{a_z}{a_x}\right)^m \geq P_{kr}. \qquad (7)$$

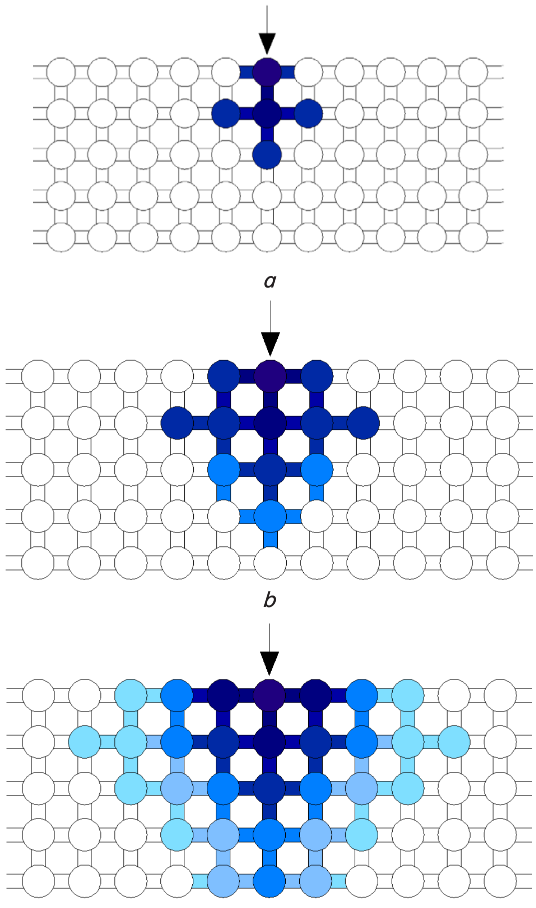

Fig. 6. Dynamics of wetted zone at discrete modeling: *a* – start of sorption process; *b* – moisture's reaching of inner surface; *c* – moisture distribution in transverse direction

Imagine a new boundary distribution as function

x=x1+x2,

where x1 is the function that described the boundary of the wetted zone without the effect of additional wetting, x2 is the function that considers effect of additional wetting.

Imagine these functions in the form

$$x1 = A1 \cdot e^{-A2z}, \quad x2 = B1 \cdot z \cdot e^{-B2z}. \tag{8}$$

Plotting for the given dependences at arbitrary values of coefficients are shown in Fig. 7.

Let us try to determine coefficients of regression equations for specific moments of the fluid distribution.

We will carry out a numerical analysis for the points, which the liquid reached in the model of discrete modeling. We will distinguish four time moments. For each moment, we distinguish coordinate of the cell by height, as well as coordinate of the cell, which the fluid reached.

We will operate with specific values, assigning them according by the depth to the thickness of material, by coordinate x – to the maximum possible parameter of fluid distribution.

It can be seen from the distribution of points that the corresponding wetted zone has a very pronounced maximum, which determines the effect of additional wetting inside the material. The developed procedure implies approximation of this effect by two functions. In this case, the points, obtained as a result of numerical experiment, artificially move so that two families of points should be formed. The first family should have the properties of exponential decreasing function, the second one – the properties of exponential function with the maximum that starts at zero value.

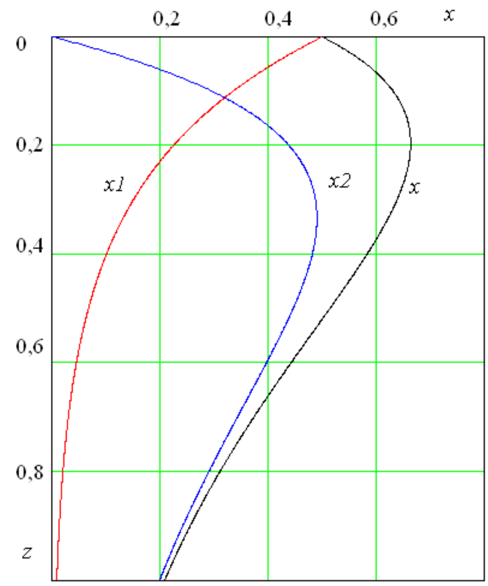

Fig. 7. Graphic images of approximating functions $x1=A1 \cdot e^{-A2 \cdot z}$, $X2=B1 \cdot z.e^{-B2 \cdot z}$, x=x1+x2

Let us consider determining the coefficients for a cotton sample at a certain moment of time. Using the method for this case produces equation of boundary of the wetted zone in the form

$$x(z) = 0,32 \cdot e^{-3,8z} + 2,6 \cdot z \cdot e^{-2,2z}. \tag{9}$$

Visual comparison can be made in Fig. 8, where the points of numerical experiment at discrete modeling and approximation by double function are presented. The graph demonstrates good correlation of continuous functions and discrete model, which makes it possible to propose it as universal for further analysis.

To determine dependence of coefficients on time, we will perform operation of regression for several other moments of time.

With the aim of finding functions of time, we will run a regressive analysis for each separately.

The points of the graph of the first function versus time are shown in Fig. 9.

When analyzing its form, we can conclude that there is a continuous function that increases and reaches certain asymptotic dependence.

Approximating function for such a case will be searched for in the form

$$f1(t) = 1 - a \cdot e^{-b \cdot t}. \tag{10}$$

Using the least squares method for the examined material produces expression

$$f1(t) = 1 - 0,99 \cdot e^{-1,46t} \approx 1 - e^{-1,46t}. \tag{11}$$

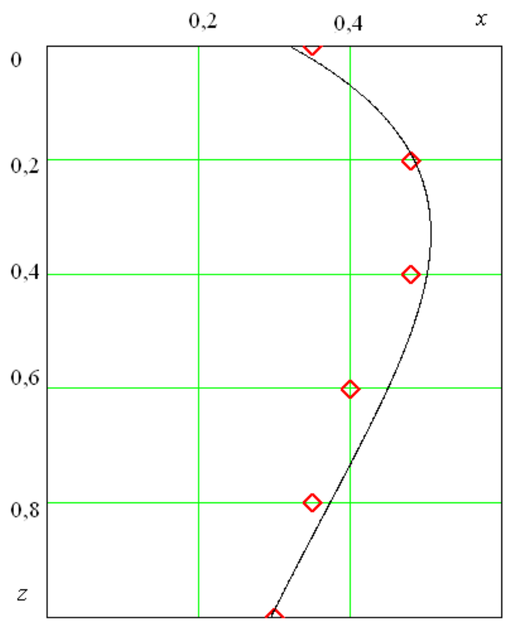

Fig. 8. Comparing general regression line to discrete modeling for time 0.4

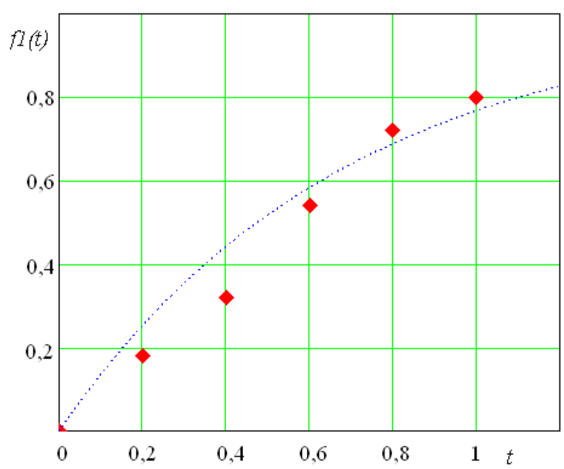

Fig. 9. The first function *f*1 versus time

Let us analyze possible dependence for the second function (Fig. 10).

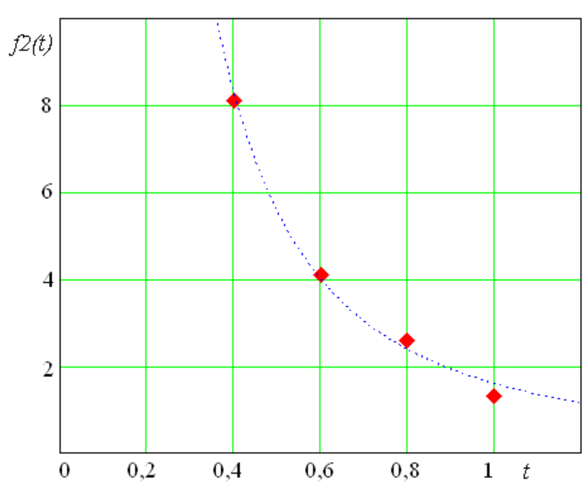

Fig. 10. Second function f2 versus time

The function starts from very large values and asymptotically approaches zero. We will search for dependence of this function on time in the form

$$f2(t)=\frac{a2}{t^{b2}}. \tag{12}$$

The solution with the use of the least squares method for this sample produces expression for function

$$f2(t)=\frac{1{,}8}{t^{1{,}6}}. \tag{13}$$

The third function takes a general form, similar to the second one (Fig. 11).

The above given analysis is used for this function, too. This function is approximated by dependence of form

$$f3(t)=\frac{a3}{t^{b3}}. \tag{14}$$

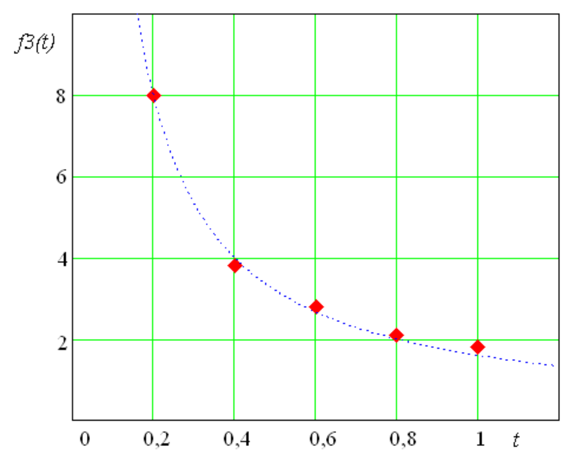

Fig. 11. Third function f3 versus time

Solution with the help of the least squares method produces expression for function

$$f3(t)=\frac{1{,}7}{t^{1{,}05}}\approx\frac{1{,}7}{t}. \tag{15}$$

The given results allow identifying separate components of the process of fluid distribution in a multi–layer textile material. Based on the obtained separate dependences, it is possible to create a general function of the fluid passage.

6. Discussion of results of determining the fluid distribution in textile materials

As a result of the conducted analysis, it is possible to argue that regression dependences for the boundary function can be written down in the form

$$x=\left(1+\frac{A3\cdot z}{t^{A4}}\right)a\cdot e^{-A1\frac{z}{t}}\cdot\left(1-e^{-A2t}\right), \tag{16}$$

where the correspondent coefficients are functions of the properties of material.

Continual dependences that determine the effect of increasing concentrations are shown in Fig. 12.

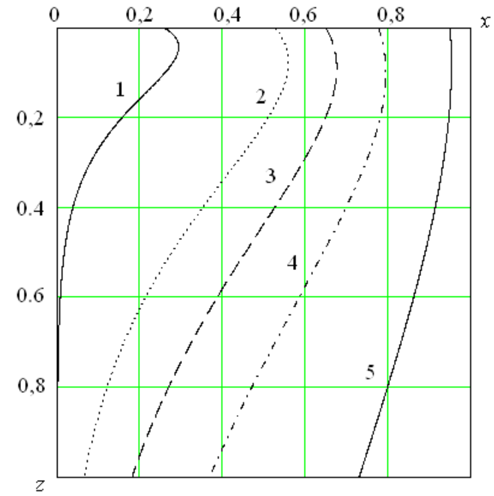

Fig. 12. Boundary of wetted zone in case $P>P_{kr}$ ($t_5>t_4>t_3>t_2>t_1$): 1 — in ten minutes, 2 — in twenty minutes, 3 — in thirty minutes, 4 — in forty minutes, 5 — in fifty minutes

The developed discrete method of modeling the fluid passage through material allows us to determine boundaries of the wetted zone of material both at its surface and in the depth for materials with arbitrary number of layers. Conducted preliminary studies [23, 25] substantiated a general approach. In this paper, this approach is applied for studying a specific material.

This approach allowed us to substantiate the effect of additional concentrations inside material. Taking this effect into account makes it possible to predict correctly the dynamics of fluid passing through textile materials.

Actual indices of a two-layered textile material were determined. Their use allows determining the concentration of fluid at the bottom layer of the material. This makes it possible to predict the effectiveness and period of using it as therapeutic textile systems.

The use of the proposed methods for a set of materials will enable the selection of material with the most rational characteristics for a particular case. Proper consideration of the obtained effects of additional wetting will make it possible to regulate the fluid passage to the body in therapeutic textile systems.

7. Conclusions

As a result of the conducted research into the fluid transfer in multi-layered textile materials, the method of discrete modeling was designed and verified.

1. The advantage of discrete analysis is the proximity of the model to the actual structure of material, which allows bringing the obtained numerical results closer to the practical ones.

2. A discrete model of fluid distribution allows determining the fluid concentration at any arbitrary point of the material.

3. As a result of the performed numerical analysis of fluid distribution in one-layered material, exponential dependences were obtained. The constants of material in this case are the exponents in these dependences, which are determined by the results of discrete modeling.

4. In the course of studying the regularities of fluid distribution in a multi-layered textile material, discrete data of changes in liquid concentration in the material were obtained. The boundaries of the wetted zone were determined.

5. The effect of additional wetting in multi-layered textile materials was determined. It is expressed by the emergence of extremum at the boundary of the wetted zone.

6. An analysis of functional dependences of the boundary of the wetted zone for two-layered textile materials used for therapeutic purposes allows determining the period of passage of exudate from the body of a patient through the material, which defines the period of functioning of such material, as well as intensity of the passage of medicinal liquid to the surface of the wound through the medical textile material that are the source data for regulating its supply.

References

1. Indushekar, R. Studies on Test Methods used to Measure Water Vapor Transmission of Fabrics by DSC and Conventional Dish Techniques [Text] / R. Indushekar // Journal of Industrial Textiles. – 2005. – Vol. 34, Issue 4. – P. 223–242. doi: 10.1177/1528083705051454
2. Van Amber, R. R. Thermal and moisture transfer properties of sock fabrics differing in fiber type, yarn, and fabric structure [Text] / R. R. Van Amber, C. A. Wilson, R. M. Laing, B. J. Lowe, B. E. Niven // Textile Research Journal. – 2014. – Vol. 85, Issue 12. – P. 1269–1280. doi: 10.1177/0040517514561926
3. Kang, Y. K. Application of Electrospun Polyurethane Web to Breathable water-proof Fabrics [Text] / Y. K. Kang, C. H. Park, J. Kim, T. J. Kang // Fibers and Polymers. –2007. – Vol. 8, Issue 5. – P. 564–570. doi: 10.1007/bf02875881
4. Holms, D. A. Waterproof Breathable Fabrics [Text] / D. A. Holms // Handbook of Technical Textiles. – Cambridge: England, 2000. – P. 282–315. doi: 10.1533/9781855738966.282
5. Goessens, T. Diffusion of Active Ingredients in Textiles [Text] / T. Goessens, B. Malengier, P. Li, R. H. De Staelen // Journal of Mathematical Modelling and Algorithms in Operations Research. – 2012. – Vol. 12, Issue 3. – P. 253–264. doi: 10.1007/s10852-012-9209-1
6. Chichani, S. A Method of Modeling Fabric Shear using Finite Element Analysis [Text] / S. Chichani, A. Guha // Journal of The Institution of Engineers (India): Series E. – 2014. – Vol. 96, Issue 1. – P. 1–7. doi: 10.1007/s40034-014-0051-z
7. Pham, C. Bioengineered skin substitutes for the management of burns: a systematic review [Text] / C. Pham, J. Greenwood, H. Cleland, P. Woodruff, G. Maddern // Burns. – 2007. – Vol. 33, Issue 8. – P. 946–957. doi: 10.1016/j.burns.2007.03.020

8. Adamson, R. Role of macrophages in normal wound healing: an overview [Text] / R. Adamson // Journal of Wound Care. – 2009. – Vol. 18, Issue 8. – P. 349–351. doi: 10.12968/jowc.2009.18.8.43636
9. Ciesielska-Wrobel, I. L. The hand of textiles – definitions, achievements, perspectives – a review [Text] / I. L. Ciesielska-Wrobel, L. Van Langenhove // Textile Research Journal. – 2012. – Vol. 82, Issue 14. – P. 1457–1468. doi: 10.1177/0040517512438126
10. Shyr, T. W. Approaches to Discriminate the Characteristic Generic Hand of Fabrics [Text] / T.-W. Shyr, J.-Y. Lin, S.-S. Lai // Textile Research Journal. – 2004. – Vol. 74, Issue 4. – P. 354–358. doi: 10.1177/004051750407400412
11. Varshney, R. K. Influence of polyester fibre fineness and cross-sectional shape on low-stress characteristics of fabrics [Text] / R. K. Varshney, V. K. Kothari, S. Dhamija // Journal of the Textile Institute. – 2011. – Vol. 102, Issue 1. – P. 31–40. doi: 10.1080/00405000903453661
12. Khoddami, A. Effect of hollow polyester fibres on mechanical properties of knitted wool/polyester fabrics [Text] / A. Khoddami, C. M. Carr, R. H. Gong // Fibers and Polymers. – 2009. – Vol. 10, Issue 4. –P. 452–460. doi: 10.1007/s12221-009-0452-7
13. Das, A. Studies on cotton-acrylic bulked yarns and fabrics. Part I: Yarn characteristics [Text] / A. Das, V. K. Kothari, M. Balaji // Journal of the Textile Institute. – 2007. – Vol. 98, Issue 3. – P. 261–267. doi: 10.1080/00405000701550163
14. Grabowska, K. E. Basic Comparison of the Properties of the Loop and Frotte Yarns,Woven and Knitted Fabrics [Text] / K. E. Grabowska, I. Ciesielska-Wrobel // Autex Research Journal. – 2014. – Vol. 14, Issue 3. doi: 10.2478/aut-2014-0009
15. Ishtiaque, S. M. Ring frame process parameters and fabric comfort. Part I – low-stress mechanical properties of fabrics [Text] / S. M. Ishtiaque, A. Das, A. K. Kundu // The Journal of The Textile Institute. – 2013. – Vol. 105, Issue 3. – P. 348–355. doi: 10.1080/00405000.2013.840413
16. Kim, H. A. Mechanical properties of worsted fabrics for emotional garment to the rapier loom characteristics [Text] / H. A. Kim, S. J. Kim // Fibers and Polymers. –2013. – Vol. 14, Issue 12. – P. 2163–2168. doi: 10.1007/s12221-013-2163-3
17. Tang, K. P. Effect of Softeners and Crosslinking Conditions on the Performance of Easy-care Cotton Fabrics with Different Weave Constructions [Text] / K. P. Tang, J. T. Fan, J. F. Zhang, M. K. Sarkar, C. W. Kan // Fibers and Polymers. – 2013. – Vol. 14, Issue 5. – P. 822–831. doi: 10.1007/s12221-013-0822-z
18. Lam, Y. L. Objective measurement of hand properties of plasma pre-treated cotton fabrics subjected to flame-retardant finishing catalyzed by zinc oxide [Text] / Y. L. Lam, C. W. Kan, C. W. M. Yuen // Fibers and Polymers. – 2014. – Vol. 15, Issue 9. – P. 1880–1886. doi: 10.1007/s12221-014-1880-6
19. Mori, M. Correlation with itchy feeling of fabric handling change by physicochemical processing of woolen fabric [Text] / M. Mori, T. Fujimoto, M. Murakami, M. Matsudaira // Fibers and Polymers. – 2013. – Vol. 14, Issue 12. – P. 2202–2211. doi: 10.1007/s12221-013-2202-0
20. Ozen, I. Multi-layered Breathable Fabric Structures with Enhanced Water Resistance [Text] / I. Ozen // Journal of Engineered Fibers and Fabrics. – 2012. – Vol. 7, Issue 4. – P. 63–69.
21. Das, B. Moisture Flow through Blended Fabrics – Effect of Hydrophilicity [Text] / B. Das, A. Das, V. Kothari, R. Fanguiero, M. D. Araujo // Journal of Engineered Fibers and Fabrics. – 2009. – Vol. 4, Issue 4. – P. 20–28.
22. Riabchykov, N. Linear mathematical model of water uptake perpendicular to fabric plane [Text] / N. Riabchykov, V. Vlasenko, S. Arabuli // Vlakna a textil. – 2011. – Issue 2 (18). – P. 24–29.
23. Schutskaya, A. Discrete two-dimensional model of moisture spreading in textile materials [Text] / A. Schutskaya, N. Suprun // Vlákna a textil. Textile Technologies. – 2015. – Issue 34. – P. 12–17.
24. Liu, X. Numerical simulation of the three-dimensional flow field in four pneumatic compact spinning using the Finite Element Method [Text] / X. Liu, X. Liu // Textile Research Journal. – 2015. – Vol. 85, Issue 16. – P. 1712–1719. doi: 10.1177/0040517514553876
25. Schutskaya, A. Discrete three-dimensional model of moisture spreading in textile materials [Text] / A. Schutskaya, N. Suprun // Vlákna a textil. Textile Technologies. – 2016. – Issue 23 (2). – P. 15–22.