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TRANSPORT
IN POLYMERS

Modeling the Directed Diffusion of Fluid through the Microchannels on the Surfaces of Polymer Films

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Abstract—The heterogeneous surface gradient micro- and macrostructures of various designs, including extensive channels, were analyzed on films of low-density polyethylene formed through the serial treatment with fluorinating and sulfuring reagents in combination with mechanical modification. Approaches to the development of systems for the directed microfluidic transfer of target compounds on film surfaces by "molecular rail channels," which is based on significant differences in the physicochemical properties of modified regions, were discussed. A mathematical model of mass transfer through the gradient surface structures of a given chemical and structural design was developed to estimate the possibility of their use for the directed transfer of target compounds.

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INTRODUCTION

Recently, the interest in structural modifications of polymer surfaces has greatly increased, a situation that is due to both the diversity of existing synthetic and biological polymers and the emerging possibilities of the "construction" of new types of polymers. Polymer structures with high resolution can be obtained through the design of reactive precursor molecules and their polymerization on the surfaces of polymers or through the self-assembly of block copolymers. This research area has developed rapidly, and recent advances in the design of polymers via photolithography, printing, self-assembly of block copolymers, or processing of thin polymer films with the use of thermal or electromagnetic fields were observed in detail in a number of articles and reviews [1–8]. Several studies in this field are of practical importance. For instance, note the jet-lithography-induced formation of a pattern on a polymer surface: a process used in the production of fibers, matrixes of microlenses [9], transformers [10], and matrixes of cells and proteins [11].

In general, the known methods for the obtainment of surface functional structures suggest the use of an inorganic or polymer support. At the same time, it is possible to obtain such structures that transform the surface layers of polymer films via polymer-analogous reactions. The films of available tonnage polymers—such as polyethylene, polypropylene, polyvinyl chloride, polyethylene terephthalate, and other polymers—may be applied in this case.

The chemical and combined methods of surface modification are used in the best-known methods for the treatment of polymers to give them positive properties [12]. The most common and traditional methods are modifications uniform across the polymer region [12] and generally do not consider the chemical and morphological diversity of the initial material surface. In addition, the purposeful formation of heterogeneous surface nano-, micro - and macrostructures in polymers of different types and configurations to impart a new complex of positive physicochemical properties is a significant fundamental goal. Such mosaic structures that result from chemical modifications in the case of the chaotic, statistical distribution of fluorinated and sulfonated structures on the surface of a polymer film provided, for instance, a marked increase in hemocompatibility [13]. Polymer films with a specified pattern of the heterogeneous regions might be useful in the production of functional film materials and devices with a flexible basis [14] and in the formation of macro- and microsized sulfonated channels for the directed transfer of liquid media via the principle of "molecular rails," which was formulated in [15], on the surface of a polymer film. However, the complex chemical and morphological design of the surface structures leads to certain difficulties in the study of the properties of the individual heterogeneous regions and the processes with their participation. Mathematical modeling of physicochemical processes, including liquid mass transfer of target compounds, may play an important role in these systems.

The purpose of this investigation was to model and research the processes of directed diffusion of fluids through the formed heterogeneous surface structures in polyethylene films.

EXPERIMENTAL

Films of low-density industrial polyethylene (Dorkhimzavod, Moscow) with a thickness of 100 μm were used in the experiments. The fluorination was performed with a mixture of elemental fluorine and helium in accordance with a developed technique [16], and sulfonation was conducted according to [17]. The modification intensity was characterized by the degrees of surface fluorination and sulfonation, C_A^F and $C_A^{SO_3H}$, respectively, and was equal to the ratio of the increase in sample mass resulting from the modifications and the surface area.

The formation of the heterogeneous surface structures with given patterns on the polymer films (straight channels and channels in the grid form) was achieved via fluorination and sulfonation and via photolithography with the use of standard techniques [18, 19] of a coating on the film surface of an alloy of nickel and chromium (nichrome). The technique included the following operations: coating the polymer surface with a metal layer of a predetermined thickness; applying a metal layer on the top of a photoresist and developing a pattern on its surface with the corresponding template, followed by developing a pattern on the underlying metal layer; etching the exposed metal layer to the surface of the initial polymer; and removing the protective film from the remaining metal layer and obtaining a metal layer with the required topography on the film. The polymer film with the pattern of the metal layer was fluorinated and the metal layer was removed via etching of the metal in order to form regions of fluorinated and nonfluorinated initial polymer. The film was sulfonated in the further experiments.

The quantitative analysis of the contents of individual elements in the surface layers of the modified polymers was performed via X-ray photoelectron spectrometry (XPS) with a JPS-9200 spectrometer (Jeol, Japan) equipped with a hemispherical analyzer and an X-ray double-anode gun. The resolution of the spectrometer was 0.9 eV on the Ag3*d* level with MgK_α X-rays. The depth of the analysis was 2 nm. The morphological changes in the surface structures were analyzed with an atomic force microscope in the tapping mode (SPM Solver, BIO NT-MDT, Zelenograd) using NSG 1 silicon probes plated with gold. (The corner radius of the needle was 10 nm.) Photographs in the visible spectrum were taken with a PO-LAM P-312 optical polarizing microscope at ×20 magnification and a CX41 optical microscope (Olympus Corporation, Japan) that were connected to a video camera. The kinetics of swelling of the sulfonated layer of surface modified LDPE in water was studied gravimetrically with full immersion of the film in distilled water. The degree of swelling of the film, *C*, was determined as the ratio of the mass of sorbed water to the mass of the sulfonated layer. The latter was calculated on the basis of the obtained experimental dependence of the thickness of the sulfonated layer on the degree of sulfonation [17]. The kinetics of moving water through the surface sulfonated channels in the LDPE film was studied gravimetrically via immersion of a film sample with a length of 100 mm and width of up to 20 mm in water to a depth of 1 mm. A linear plot corresponding to the steady-state rate of water movement through the surface sulfonated channels of polyethylene was chosen from the obtained dependence of the increase in the sample mass on time and was used to determine the rate of the process as the ratio of the increase in the sample mass to the corresponding time.

RESULTS AND DISCUSSION

Previously, we investigated the formation of heterogeneous surface structures by using the surface modification of films with intermediate deforming operations, heat treatment, and dosage destruction of the surface layer [14]. Each of these methods possessed limitations and disadvantages. For example, the formation of sulfonated channels according to the method of crazing under uniaxial tension of the preliminary fluorinated films of polyolefins [20–22] resulted in channels with widths of several micrometers. However, these channels were always strictly normal to the direction of stretching and possessed the known curvature and limited lengths (up to ~50 μm). The mechanical method of degrading the fluorinated surface layer with subsequent sulfonation of the exposed initial polymer sufficiently deformed the film surface, thereby reducing its strength. The method of fluorination and sulfonation of polymer films with intermediate application of photolithography techniques was the most general in terms of the possible implementation of various schemes of heterogeneous surface structures.

Figure 1 presents some ways to obtain fluorinated and sulfonated bands (channels) on the surface of an LDPE film via photolithography. (The pictures were taken with a POLAM R-312 optical polarizing microscope.) This method made it possible to develop sulfonated microchannels with widths of 85 μm or more and macrochannels with distinct boundaries on the fluorinated film surface. (The degree of sulfonation in the region of a channel was determined from the degree of sulfonation of a control sample.) The clarity of the boundary between the fluorinated surface and sulfonated region of the channel (Fig. 1–IV–c) made it possible for the prefluorinated LDPE surface to be sulfonated 100–200 times slower than the surface of the initial polymer [13, 23]. In addition, the pictures (Fig. 1–IV) clearly show that the LDPE surface sub-

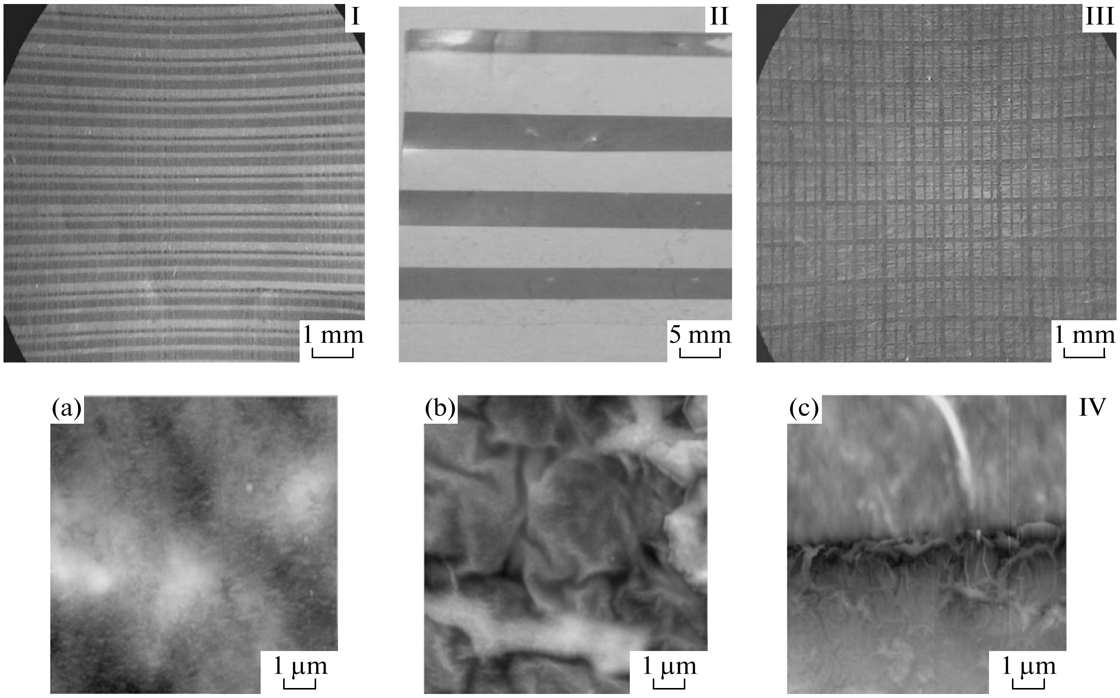

Fig. 1. Images of the surfaces of LDPE samples with (I) microchannels and (II) macrochannels and (III) channels in the form of a grid. The dark bands are sulfonated channels ($C_A^{SO_3H} = 2.1 \times 10^{-3}$ kg/m^2); the light bands are fluorinated surfaces $C_A^F = 4.1 \times 10^{-4}$ kg/m^2). (IV) AFM image of fluorinated and sulfonated regions of the sample with microchannels: (a) fluorinated region, (b) sulfonated region, (c) the boundary between the (top) fluorinated and (bottom) sulfonated regions of the sample; the size of the scanned area is 10 × 10 μm.

jected to sulfonation (Fig. 1–IV–b) possesses a more developed microrelief than that of the fluorinated surface. Note that the method can be implemented without prior fluorination of the surface of the polymer film, but only with sulfonation in the regions between deposited metal strips. However, in this case, the sulfonation of a metal strip is immediately started together with the main process of sulfonation the polymer, a situation that does not allow minimization of the appropriate distance between sulfonated channels at the same depth of sulfonation in comparison to that of the prior fluorination and leads to a more blurry boundary between the sulfonated region and the initial polymer because of the amorphous–crystalline structure of the initial polymer. All other things being equal, the losses of different fluids due to improper diffusion through the fluorine-containing film layer during the diffusion transfer along the sulfonated channels are lower than those for the initial film of the polyolefin.

There is an application of the significant differences in the physicochemical properties of the fluorinated and sulfonated regions for polymer films with fluorinated and sulfonated surfaces with the given configurations. The sulfonated regions, as opposed to the fluorinated regions, could, for instance, absorb a large quantity of water, and the amount of sorbed water is directly proportional to the degree of sulfonation. Figure 2 presents the kinetics of swelling of the LDPE films with different degrees of sulfonation in water.

The equilibrium saturation of the films with water is achieved in about a day, as shown by Fig. 2. However, the sorption of water at the initial stage of the process (curves *1*, *2*) is fairly intense owing to the large affinity of sulfo groups for water. For example, swelling of the sulfonated film ($C_A^{SO_3H} = 5.8 \times 10^{-3}$ kg/m^2) to 60% of the equilibrium value was accomplished over 1 h. This process proceeds a little bit slower for the film with a lower degree of sulfonation, a result that is due to a lower content of sulfo groups. The control samples of the initial LDPE film and the LDPE film subsequently fluorinated ($C_A^F = 4.7 \times 10^{-4}$ kg/m^2) and sulfonated ($C_A^{SO_3H} = 0.11 \times 10^{-3}$ kg/m^2) during the experiment under the same conditions in water undergo practically no swelling (curves *3*, *4*). The experimental results make it possible to determine several parameters of the mass transfer of water for the sulfonated film layer. For example, the diffusion coefficient is $D = 2.5 \times 10^{-11}$ cm^2/s and the solubility coefficient is $S = 0.6$ g/cm^3 at $C_A^{SO_3H} = 5.8 \times 10^{-3}$ kg/m^2, while coefficients D and S are 3.3×10^{-12} cm^2/s and 0.4 g/cm^3, respectively, for $C_A^{SO_3H} = 2.1 \times 10^{-3}$ kg/m^2. The amount of water adsorbed by a film is roughly proportional to the degree of sulfonation. This result is confirmed by a

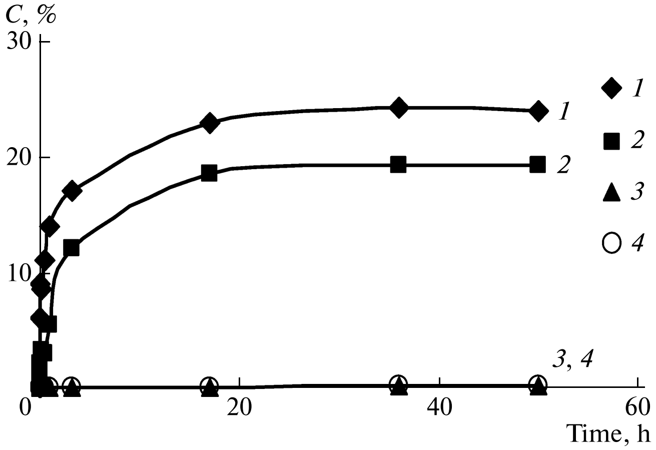

Fig. 2. Kinetics of swelling in water (*1*, *2*) by LDPE films with degrees of sulfonation of $C_A^{SO_3H}$ = (*1*) 5.8×10^{-3} and (*2*) 2.1×10^{-3} kg/m^2, (*3*) by the initial LDPE film, and (*4*) by the subsequently fluorinated ($C_A^F = 4.7 \times 10^{-4}$ kg/m^2) and sulfonated ($C_A^{SO_3H} = 1.1 \times 10^{-4}$ kg/m^2) LDPE film.

comparison of the sulfur contents and the carbon contents (according to XPS, see the table) in the surface layers of sulfonated films (a depth of scanning of 2 nm).

According to the data, one sulfo group is introduced per 28–30 atoms of the polymer macromolecule at low degrees of sulfonation. The ratio increases to one sulfo group per six carbon atoms with an increase in the time of sulfonation. However, these data refer to the top of the sulfonated layer, constituting ~1% of the entire depth of sulfonation. The ratio of the amount of sulfo groups to the number of carbon atoms of the polymer chain decreases for the deeper layers of the polymer in the sulfonation region owing to the dependence on the rate of diffusion of the sulfuring agent (sulfuric anhydride) into the polymer. However, the dependence of the amount of introduced sulfo groups on the duration of sulfonation is maintained for each layer.

The ratio of the elements in the sulfonated surface layers of LDPE films

Degree of sulfonation, kg/m^2	Thickness of the sulfonated layer, μm	Content, at %		
		carbon	sulfur	oxygen
0	–	100	–	–
0.2×10^{-3}	0.2	86.0	2.8	10.1
1.2×10^{-3}	0.8	74.1	5.7	17.6
3.5×10^{-3}	2.5	56.5	10.1	29.8

The experimental data confirm that channels in the polymer films with heterogeneous surface structures are established (at the corresponding configuration of sulfonated regions) for the transfer of water and aqueous solutions directly on the surface of the chemically inert and stable fluorinated LDPE film (based on the principle of “molecular rails”). A film with sulfonated channels in different configurations with a width of tens of micrometers could be defined to some extent as a microfluidic system with the diffusion mechanism of mass transfer [24].

The optimal correlation of the times of fluorination and sulfonation is an important prerequisite for the efficient formation of sulfonated channels because the sulfonation proceeds quite vigorously and to a great depth. Figure 3 presents the features of the process. The duration of sulfonation and the distance between the channels should be chosen to eliminate the overlap of the sulfonated regions by fluorinated regions of the polymer film and the mixing of fluids (which may differ in composition and type) that are being transported through the adjacent channels. Consequently, the mathematical model of the kinetics of sulfonation of the polymer film surface possessing alternating fluorinated regions and nonfluorinated channels was performed with allowance for the previously developed models of fluorination and sulfonation of polymer films [25–27].

Experimental data on the ratio of the sulfonation rates of initial and prefluorinated LDPE films [13, 22] make it possible to assume that the penetration of the diffusant (sulfuric anhydride) into the fluorinated regions can be disregarded. The frontal-diffusion model can be used in this case [12], and the depth and rate of the penetration of the diffusant into the polymer through the unmodified regions depend only on diffusion coefficient D_R^* of sulfuric anhydride (the reduced diffusion coefficient, which allows for the chemical reaction of the diffusant and the polymer) and the time of sulfonation and are not associated with the sizes of the fluorinated and sulfonated regions.

After the conventional boundaries of fluorinated regions (*2*) are reached, there is a transition from frontal movement of the diffusant to multidirectional penetration deep into the polymer, including the regions located under fluorinated regions I. Time τ_1 required for the diffusant to reach the conditional depth of the fluorinated regions was estimated according to the obtained formula

$$\tau_1 = \frac{h^2}{4D_R^* B_S}, \qquad (1)$$

where B_S is a parameter dependent on the degree of sulfonation.

After the conditional depth of fluorinated regions was reached, the rate of penetration gradually decreased because the rate of diffusant uptake was

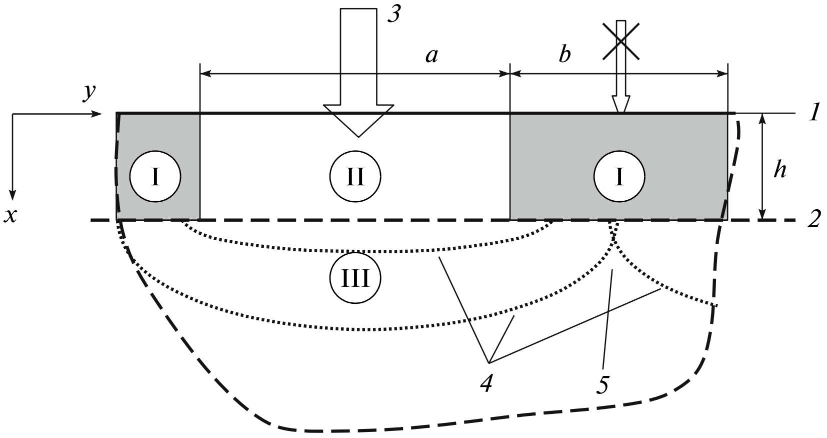

Fig. 3. Scheme of sulfonation of the polymer with the fluorinated regions preformed on the surface. Shown in the cross section of the film, the *y* axis is matched with the surface of the polymer *1* and the *x* axis is perpendicular to the surface of the polymer film; *a* is the width of the channel in the initial polymer being sulfonated, *b* is the width of the fluorinated region, *h* is the depth of the fluorinated layer; *3* is the general conditional depth of fluorination; I indicates the fluorinated regions of the polymer into which the sulfuric anhydride barely penetrated (indicated by the crossed arrow); II is the region of the frontal penetration of sulfuric anhydride into the polymer, whose direction is indicated by the large arrow; III is the region of multidirectional diffusion of sulfuric anhydride; *4* are isolines of levels of equal attachment of sulfuric anhydride according to the concentration of bound sulfo groups, C_R; and *5* is the point of overlapping of the isolines under the fluorinated regions.

constant, and the size of the region for possible diffusion increased. The final rate of penetration relative to the initial rate of penetration decreased $(a + b)/b$ times.

In addition, time τ_2 was required for sulfonated regions of the polymer under fluorinated regions to fuse. The equation for τ_2 has the form

$$\tau_2 = \frac{\left(h + \frac{\pi a}{8} + \frac{b}{2}\right)^2}{4 D_R^* B_S} \qquad (2)$$

Expressions (1) and (2) made it possible to estimate the durations of the sulfonation stages for more accurate matching of the sulfonated channels to specific chemical and structural designs and for exclusion of their overlapping under fluorinated regions. For example, the calculations of the sample presented in Fig. 1—I (a degree of fluorination of 4.1×10^{-4} kg/m^2, a minimum width of fluorinated regions of 100 μm, a depth of 0.4 μm) revealed that, for degrees of sulfonation of 2.1×10^{-3} and 5.8×10^{-3} kg/m^2, the extension of the sulfonated channels under the fluorinated layer (Fig. 3, region III) does not exceed 1.5 and 4.5 μm, respectively, and the depths of fluorinated channels are 2.0 and 5.0 μm, respectively. This outcome implies that the size of the fluorinated regions between the sulfonated channels can be decreased to 5—15 μm.

Mathematical modeling of the mass transfer of fluids (for instance, distilled water) through the surface sulfonated channels in the polymer film was performed (Fig. 4). The configuration of such channels may be varied. For example, channels can be in the form of a single channel (Fig. 4—I), a single channel with duplication (Fig. 4—III), and a multichannel system in the form of intersecting mutually perpendicular channels (Fig. 4—II). The influence of the solvent on the kinetics of swelling of the films of block copolymers containing micellar or lamellar regions was recently demonstrated [28]. This effect [28] was not implemented in the considered case during the absence of swelling of the initial and fluorinated parts of the polymer in water.

The directions of diffusion flow for the three-dimensional single-channel model of mass transfer are presented in Fig. 4—I. To qualitatively describe the diffusion process and to identify the key model parameters, the system was simplified from a three-dimensional model to a two-dimensional version in the *Y0X* plane. The following system of equations was obtained in this case:

$$\begin{cases} C(x, y;\, t)|_{Gin} = C_1^\infty = \text{const.} \\ \left.\dfrac{\partial C(x, y;\, t)}{\partial t}\right|_{G_1} = D_1\left.\left(\dfrac{\partial^2 C(x, y;\, t)}{\partial x^2} + \dfrac{\partial^2 C(x, y;\, t)}{\partial y^2}\right)\right|_{G_1} \\ \left.\dfrac{\partial C(x, y;\, t)}{\partial t}\right|_{G_2} = D_2\left.\left(\dfrac{\partial^2 C(x, y;\, t)}{\partial x^2} + \dfrac{\partial^2 C(x, y;\, t)}{\partial y^2}\right)\right|_{G_2} \\ D_1\left.\dfrac{\partial C(x, y, z;\, t)}{\partial y}\right|_{G_{\text{out}2}} = D_2\left.\dfrac{\partial C(x, y, z;\, t)}{\partial y}\right|_{G_{\text{out}2}} \\ C(x, y;\, t = 0)|_G = 0, \\ C(x, y;\, t)|_{G_1} \le C_1^\infty, \quad C(x, y;\, t)|_{G_2} \le C_2^\infty \end{cases} \qquad (3)$$

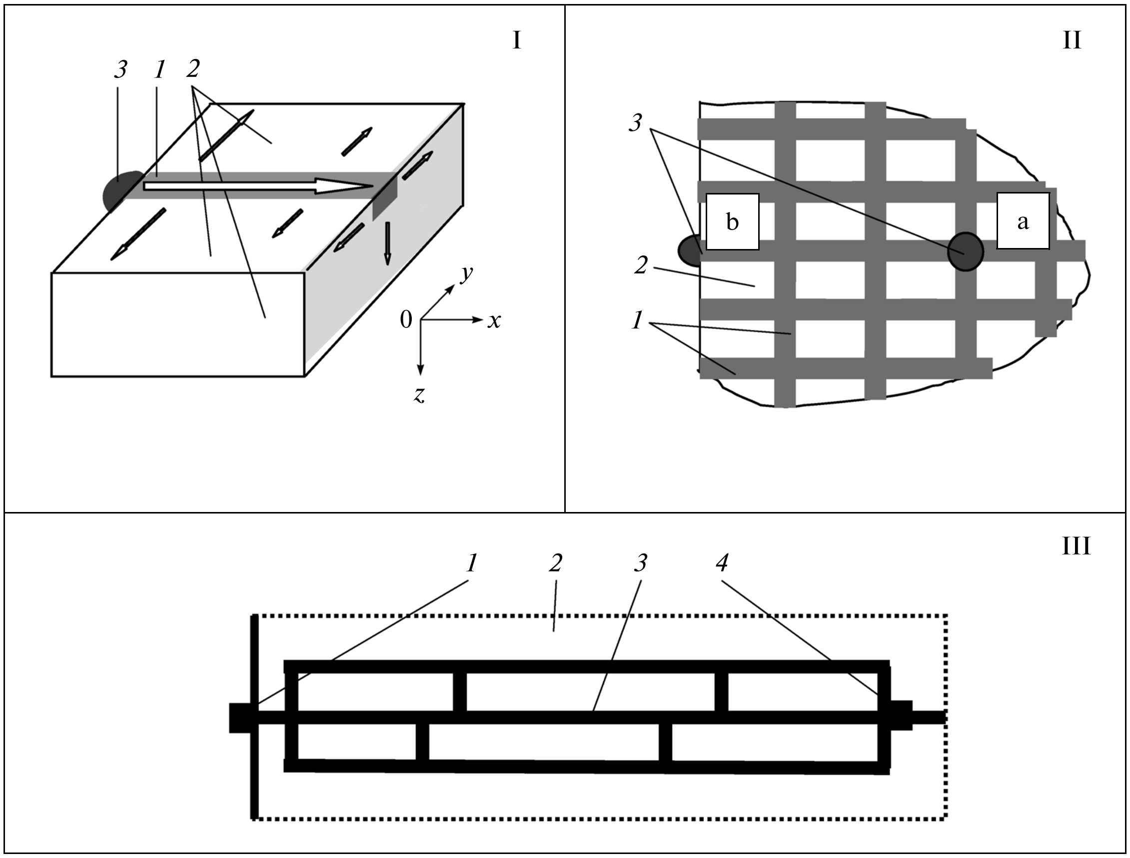

Fig. 4. (I) Single-channel model of mass transfer of the diffusant in surface sulfonated channel *1* on polymeric support *2* from a reservoir with diffusant *3*. The large arrow shows the direction of diffusion flow; the small arrow shows the possible minor diffusion perpendicular to the main flow directions. (II) Multichannel system of sulfonated channels *1* on polymeric support *2* with different types of diffusant uptake *3*: (a) central uptake, (b) uptake from the edges. (III) Single-channel system of diffusant transfer with duplication: (*1*) the point of diffusant uptake, (*2*) the polymer support, (*3*) the sulfonated channel with duplication, (*4*) the point of diffusant indication.

The variation in calculation of the isolines $C(x, y; t) = 0.2C_1^{\infty}$ indicated the movement of the diffusant along the channel on the scale of relative values $(2x/a, 2y/a)$ for the relative diffusion times $\bar{t} = \frac{4D_1t}{a^2}$ that are listed in Fig. 5.

The diffusion of water for the selected design of sulfonated regions in the form of straight channels is an almost frontal expansion through the channel. The theoretical modeling of the kinetics of movement of the diffusant along the channel according to Fig. 5 made it possible to use a well-known front model [29] as a first approximation. The front model was developed to describe the diffusion of a semi-infinite reservoir in a semi-infinite space. This model was previously adapted for the calculation of integral characteristics of the degree of surface modification during the fluorination of various types of polymers [25, 27]. The calculation formula of this model in terms of the problem of studying the kinetics of movement of water through channels is

$$C_S^{H_2O} = \frac{m_{H_2O}}{S} = 2K_{ads}\sqrt{\frac{Dt_{ads}}{\pi}} = \text{const}\sqrt{t_{ads}}, \quad (4)$$

where $C_S^{H_2O}$ is the conditional degree of swelling of the LDPE sample (in kg/m^2), equal to the ratio of the mass of water mass adsorbed by the sulfonated sample, Δm, to the area of the modified surface of the sample, S; m_{H_2O} is the mass of the water adsorbed by the sulfonated sample (in kg); D is the diffusion coefficient of water in the sulfonated LDPE region (in m^2/s); S is the area of the modified surface of the sample (in m^2); K_{ads} is a multiplicative coefficient describing the rate of water penetration in the sulfonated layer of the LDPE sample and the maximum possible concentration of water adsorbed in this layer (in kg/m^3); and t_{ads} is the time that has elapsed since the beginning of the sorption process.

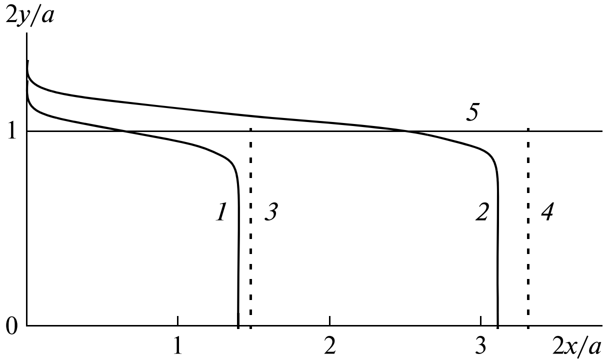

Fig. 5. Results of calculations of the diffusant movement through the sulfonated channel according to system of equations (3) on a dimensionless scale: (*1, 2*) isolines of equal concentrations of the diffusant for the relative diffusion times $\bar{t} = 1$ and 3, respectively, (*5*) boundary of the channel; (*3, 4*) results of the calculations of front model (4) for the same relative times of diffusion.

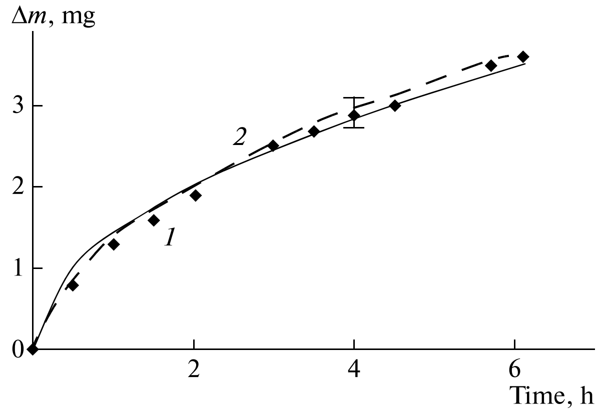

Fig. 6. Kinetic dependence of the mass of water adsorbed by the sulfonated LDPE sample, Δm, on the time of adsorption, t. The points and the solid curve *1* are experimental data; the dashed line *2* is the calculation according to model (4).

Coefficient K_{ads} depends on the degree of sulfonation of the sample adsorbing water or another fluid. The experimental data on the kinetics of water sorption by the sulfonated layer of an LDPE sample ($C_A^{SO_3H} = 5.8 \times 10^{-3}$ kg/m^2) with a volume of 20 × 100 × 0.1 mm immersed 1 mm into water on its narrow side and the theoretical curve obtained according to Eq. (4) are presented in Fig. 6.

The results shown in Fig. 6 indicate that the calculations made via formula (4) match well with the experimental data, i.e., make it possible to accurately predict the kinetics of movement of the diffusant through the sulfonated channel.

The multichannel system with intersections modeled in form of a grid with cells was possible for the directed diffusion along the sulfonated channels of heterogeneous modified polymer films. Typical examples of diffusant uptake into the channel system are given in Fig. 4—II.

The dependence on time t_n required to reach a point (node) located at a distance of n links from the reservoir (point a or b) was obtained for both variations of diffusant uptake:

$$t_n = Kn^2 t_{\text{step}}, \tag{5}$$

Here, K is a coefficient depending on the variation of diffusant uptake ($K = 4$ or 2) and t_{step} is the time of diffusant transfer on the length of the cell link through the single channel:

$$t_{\text{step}} = \frac{d^2}{4D_R^* B_R} \tag{6}$$

Here, d is the size of the channel cell (the length of the cell side) and B_R is a dimensionless parameter depending on the selected concentration level of the diffusant in the channel at the point of indication that, when achieved, shows that the target connection has been obtained. Parameter B_R depends on ratio $\frac{C}{C^\infty}$, i.e., the ratio of the selected concentration level of the diffusant to the maximum possible value:

$$B_R = \left\{2\operatorname{argerf}\left(1 - \frac{C}{C^\infty}\right)\right\}^2 \tag{7}$$

Coefficient K in Eq. (5) changes with variation in the topology of the system; however, the quadratic dependence remains.

Let us compare expression (5) and the formula for $t_{1,n}$, the time for the diffusant to reach the point (node) located at a distance of n links from the reservoir (source) of the diffusant during the central uptake into a single-channel system without intersections of channels:

$$t_{1,n} = 2nt_{\text{step}} \tag{8}$$

The difference in time required for the front to reach a node situated at a distance of d links from the diffusant reservoir for the single-channel and multichannel models can reach two or more orders of magnitude in the branched-channel system (the cell size of the system channel, d, is much less than the distance from the reservoir to the target point of indication, l: $d \ll l$):

$$\frac{t_n}{t_{1,n}} = 2n = \frac{2l}{d} \gg 1 \tag{9}$$

The advantage of single-channel systems (with possible duplication for guaranteed delivery to the target by multiple parallel channels and a few jumpers, Fig. 4—III) over multichannel systems with intersections (a network) is obviously related to both the rate of delivery to the target and the diffusant consumption.

CONCLUSIONS

The experimental results on the formation of gradient surface systems in the form of channels on the surfaces of polymer films and the mathematical modeling of directed mass transfer of fluids through these systems revealed the possibility of their use for directed transfer of substances via “molecular rails.” The formed sulfonated channels possess distinct boundaries that can decrease the width of the fluorinated region between such channels to 5–15 μm. The surface gradient micro- and macrostructures in the polymers formed with the main possible and preferred flows of directed transfer of the target compounds are based on single-channel systems with duplication in the case of a small number of reservoirs. These findings and approaches are obviously correct for other channel systems in which the movement of the diffusant is subject to the laws of mass transfer.

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