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Equation for the Kinetics of Sorption of Heavy-Metal Ions on Synthetic Aluminosilicates

P. S. Gordienko^a, I. A. Shabalin^a, S. B. Yarusova^{a,b,*}, I. G. Zhevtun^a, and O. S. Vasilenko^a

^a Institute of Chemistry, Far Eastern Branch, Russian Academy of Sciences, Vladivostok, 690022 Russia

^b Vladivostok State University of Economics and Service, Vladivostok, 690041 Russia

*e-mail: yarusova_10@mail.ru

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Abstract—A kinetics equation for topochemical reactions is obtained and used to analyze processes of the sorption of heavy-metal ions by sorbents based on nanostructured synthetic aluminosilicates (i.e., ion-exchangers whose mechanism of sorption is associated with ion exchange) while sorption isotherms are described by the Langmuir equation. It is established that the experimental results on the kinetics in all the investigated cases differ by negligible deviations from those obtained according to the proposed equation throughout the period of analysis.

Keywords: kinetics equation, sorption, sorbents

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INTRODUCTION

When investigating the kinetics of chemical reactions in heterogeneous systems, including the topochemical reactions of sorption and desorption processes, the main parameters characterizing the process are characteristic kinetic constants determined using empirical equations that describe experimental data. The time parameters of the chemical processes of sorption are important not only to adjust the optimum parameters for industrial technologies, but also to select ways of removing heavy-metal ions from living organisms with sorbents. Such empirical dependences, which contain the minimum number of variables and describe the kinetics of a process within a predetermined time period with the fewest deviations from experimental data, are crucial for investigating the kinetics of topochemical reactions.

Formal kinetics equations normally have a time dependence, e.g., the degree of a reaction's completeness (α); the current value of the sorption capacity (A_t) or its relative value equal to A_t/A_m , where A_m is the sorption capacity under equilibrium conditions; and other parameters. The applied formal kinetics equations are assumed to meet certain requirements, i.e., to describe experimental data in the predetermined time period of the investigated process. The time dependences of the completeness of a reaction (α) or the relative value of the sorption capacity are often described by the Kolmogorov–Erofeev equation in exponential form:

$$\alpha = 1 - \exp(-kt^n), \quad (1)$$

where α is the relative progress of the investigated process (ranging from 0 to 1); k is the generalized constant of the reaction rate; t is the duration of the process; and n is a kinetic parameter.

Using Eq. (1) in the form of linear dependence

$$\ln(-\ln(1 - \alpha)) = \ln k + n \ln t, \quad (2)$$

we determine rate constant K of the investigated process:

$$\ln k = -n \ln K,$$

so

$$K = \exp\left(-\frac{\ln k}{n}\right), \quad (3)$$

where K has the dimension of (time)⁻¹. According to the traditional definition of the type of reaction, this dimension of the reaction rate constant corresponds to chemical processes with reactions classified as first order. When applying the Kolmogorov–Erofeev equation, n is considered not only an index of the chemical reaction's order, but also the kinetic value of the investigated heterophase system that characterizes such physical processes as diffusion and crystal growth rate. To clearly give either physical or chemical sense to the constants in kinetic equations, some researchers analyze different models of topochemical reactions and introduce additional parameters to the proposed equations, e.g., the ratio of the reaction product volume to reagent z in the anti-Giësting–Brownstein equation

$$\frac{1}{z} + \frac{2}{3}\alpha - (1 + \alpha z^{2/3}) = kt \quad (4)$$

and the anti-Valency–Carter equation

$$\frac{1}{z} + \frac{2}{3}\alpha - \frac{(1 + \alpha z)^{2/3}}{z} = kt \quad (5)$$

or reaction homogeneity factor m in the universal Akulov equation

$$\frac{1}{\alpha^m} \frac{1 - (1 - \alpha)^{1-m}}{1 - m} = kt \quad (6)$$

and other non-sizable parameters that are not always easy to find experimentally.

When investigating the processes of heavy-metal ion sorption from aqueous solutions under nonequilibrium conditions by the sorbents containing natural or synthetic zeolites, resins, and cation-exchangers, the current values of sorption capacity depend on the duration of sorption. The mechanism of sorption for many of these sorbents is based on cation exchange, while the sorption isotherms are often described by the Langmuir equation based on the law of mass action and used to analyze sorption processes:

$$A_t = A_m k C_{\text{eq}} \frac{1}{1 + k_L C_{\text{eq}}}, \quad (7)$$

where k_L (L mmol^{-1}) is the Langmuir constant and C_{eq} (mmol L^{-1}) is the equilibrium concentration of the sorbate.

In deriving Eq. (7), Langmuir considered equilibrium conditions where the rates of sorption and desorption were identical ($V_s = V_d$), i.e., the time factor was indirectly included in the sorption mechanism. In deriving (7), the rate of the reverse reaction (desorption) was assumed here to be independent of the concentration of in a solution, which contradicted existing concepts of equilibrium processes. Rate of sorption V_s was

$$V_s = k_1 C \left(1 - \frac{A_t}{A_m}\right), \quad (8)$$

where C is the equilibrium concentration of the sorbate in the solution, mmol L^{-1} ; $\frac{A_t}{A_m}$ is the relative sorption capacity; $\left(1 - \frac{A_t}{A_m}\right)$ is the relative number of ionic sites capable of exchange; and k_1 is a constant. Rate of desorption V_d was

$$V_d = k_2 \frac{A_t}{A_m}, \quad (9)$$

where k_2 is a constant.

EXPERIMENTAL

The kinetic equation for the investigated processes was derived with allowance for several assumptions. The first of these was that a number of substituted active sites A_t in the sorbent depended not only on concentration C of the sorbate in the solution, but also on duration of sorption t , which was confirmed experimentally. Then

$$A_t = k_1 C t \left(1 - \frac{A_t}{A_m}\right), \quad (10)$$

while the desorption of the sorbate, in contrast to the assumptions made in deriving Eq. (7), was taken to depend on the concentration of the sorbate in a solution and the relative value of the sorbent's sorption capacity:

$$A_t = k_2 C \frac{A_t}{A_m}. \quad (11)$$

Under these assumptions, the equality of A_t in Eqs. (10) and (11) was determined, allowing us to obtain the time dependence of the current value of A_t :

$$A_t = A_m k t \frac{1}{1 + k t}, \quad (12)$$

where k is the constant of the dimension of $(\text{time})^{-1}$; t is time (duration); and A_m is the maximum sorption capacity of the sorbent. As follows from Eq. (12), constant k can be determined both by calculating the experimental dependences of A_t on t according to the equation

$$k = \sum \frac{\frac{A_t}{t} \left(\frac{1}{A_m - A_t}\right)}{N}, \quad (13)$$

where N is the number of A_t values at the corresponding duration of sorption, and graphically by presenting the experimental data on kinetics in the form of the linear dependence of $\frac{1}{A_t}$ on $\frac{1}{t}$:

$$\frac{1}{A_t} = \frac{1}{A_m} + \frac{1}{k t A_m}, \quad (14)$$

where $1/A_m$ is the value of the ordinate when $t \rightarrow \infty$; k is determined from the line's slope or using the equation obtained via least-squares processing of the experimental results:

$$y = a + b x, \quad (15)$$

where $a = 1/A_m$, $b = (1/A_m)(1/k)$, and $k = a/b$.

If the investigated topochemical process corresponds to the mechanism described by the Langmuir equation, Eq. (12) with constant k must describe the kinetics throughout the time interval, as was confirmed in analyzing the kinetics data [1–5].

Table 1. Dependence of sorption capacity on time at different temperatures for the sorption of Cs⁺ ions by aluminosilicates KAlSiO₄ · H₂O and KAlSi₅O₁₂ · 2.7H₂O [1]

<i>T</i> , °C	<i>t</i> , min	KAlSiO ₄ · H ₂ O				KAlSi ₅ O ₁₂ · 2.7H ₂ O			
		<i>k</i> , min ⁻¹	Δ, %	<i>A</i> _{<i>c(t)</i>} (cal.), mmol/g	<i>A</i> _{<i>c(t)</i>} (exp.), mmol/g	<i>k</i> , min ⁻¹	Δ, %	<i>A</i> _{<i>c(t)</i>} (cal.), mmol/g	<i>A</i> _{<i>c(t)</i>} (exp.), mmol/g
20	1	38	0.80	0.2605	0.2626	56	2.1	0.2790	0.2732
	5		0.90	0.2660	0.2634		0.10	0.2829	0.2832
	10		0.07	0.2666	0.2668		0.07	0.2834	0.2836
	30		0.14	0.2671	0.2667		0.03	0.2838	0.2837
	60		0.18	0.2672	0.2667		0.07	0.2839	0.2841
	120		0.27	0.2673	0.2666		0.10	0.2839	0.2842
	240		0.03	0.2673	0.2674		0.07	0.2839	0.2840
40	1	18	2.90	0.2575	0.2650	83	0.98	0.2857	0.2829
	5		0.96	0.2689	0.2663		0.13	0.2873	0.2869
	10		1.36	0.2703	0.2666		0.07	0.2876	0.2878
	30		1.80	0.2713	0.2664		0.27	0.2878	0.2886
	60		3.50	0.2716	0.2712		0.03	0.2879	0.2878
	120		0.51	0.2717	0.2703		0.24	0.2879	0.2872
	240		0.03	0.2718	0.2719		0.03	0.2879	0.2880
70	1	6.2	7.53	0.2393	0.2588	25.5	1.30	0.2781	0.2818
	5		0.66	0.2693	0.2711		0.06	0.2868	0.2870
	10		4.19	0.2756	0.2645		0.50	0.2879	0.2864
	30		1.72	0.2765	0.2718		0.13	0.2887	0.2883
	60		2.02	0.2772	0.2717		0.13	0.2889	0.2885
	120		1.12	0.2776	0.2745		0.03	0.2890	0.2891
	240		0.07	0.2778	0.2780		0.70	0.2890	0.2868

For any proposed empirical kinetics equation, we must provide the rationale of the physical sense for the constant values it contains. In Eq. (12), the inverse value of constant *k* corresponded to the duration of sorption at which half the active sites reacted (i.e., the cation exchange reaction occurred), which can be easily be checked experimentally. It is easy to compare the kinetic properties of sorbents using this parameter. The experimentally obtained values of *k* at different temperatures of the investigated process allowed us to calculate the energy of activation and variations in the thermodynamical parameters of a sorbent–sorbate system using the Arrhenius equation:

$$G = -TR \ln k. \quad (16)$$

The Langmuir constant (*k_L*) in Eq. (7) and constant *k* in Eq. (12) characterize the sorbent explicitly, by sorption capacity first and kinetic properties second.

RESULTS AND DISCUSSION

The authors of [1] provided data (Table 1) on the kinetics of sorption of cesium ions from aqueous solutions by nanostructured aluminosilicates (S : L =

1 : 40; *C* = 7.67 mmol L⁻¹), according to which the rate of cation exchange between the sorbent and the solution was very high. Within one minute (discounting filtration time), the sorption capacity of KAlSiO₄ · H₂O and KAlSi₅O₁₂ · 2.7H₂O was no less than 95% of its equilibrium value (Table 1). A similar dependence was obtained earlier using synthetic potassium aluminosilicate KAlSi₃O₈ · 1.5H₂O [6].

Using the maximum sorption capacity values (*A_m*) of aluminosilicates at sorption temperatures of 20, 40, and 70°C (0.2674, 0.2717, and 0.2780 mmol g⁻¹, respectively, for KAlSiO₄ · H₂O and 0.2840, 0.2880, and 0.2891 mmol g⁻¹ for KAlSi₅O₁₂ · 2.7H₂O, respectively), and the values of sorption capacity at times of 1, 5, and 10 min (Table 1), we calculated the values of the constant *k* (min⁻¹) of kinetic equation (12) using Eq. (13) for KAlSiO₄ · H₂O and KAlSi₅O₁₂ · 2.7H₂O. Table 1 gives both the calculated and experimental values of sorption capacity, along with the differences between them (Δ, %) and the calculated values of *k* (min⁻¹) for each temperature. The greatest difference between the sorption capacities determined experimentally and calculated according to Eq. (12) was no

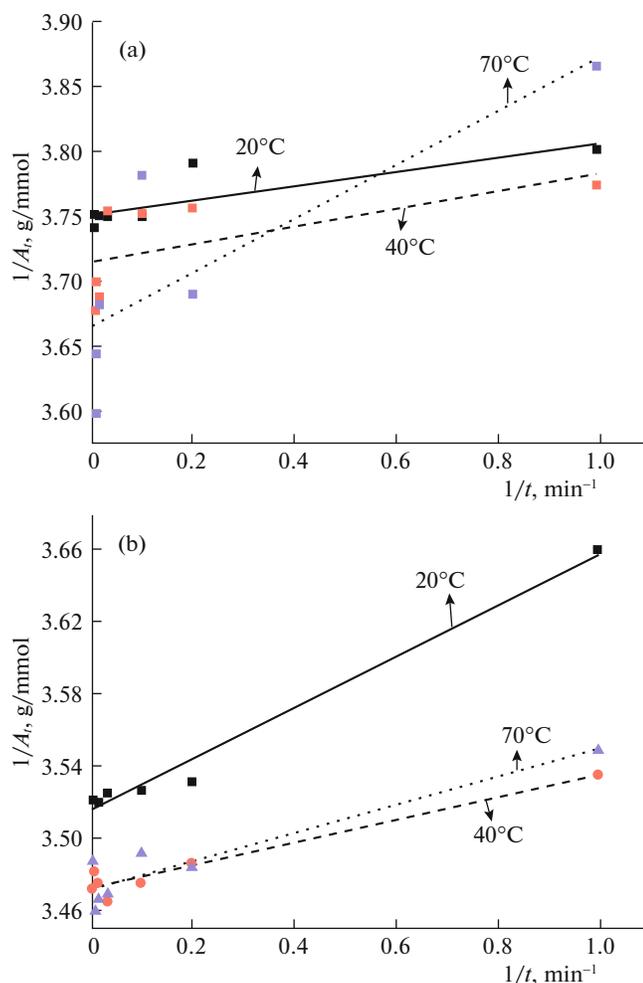


Fig. 1. (Color online) Dependences of the inverse sorption capacity of (a) $\text{KAlSiO}_4 \cdot \text{H}_2\text{O}$ and (b) $\text{KAlSi}_5\text{O}_{12} \cdot 2.7\text{H}_2\text{O}$ toward Cs^+ ions from $1/t$ at different temperatures [1].

more than several percent. It was observed at only a few points, so it must be attributed to measuring error in the course of our experiments. Most of the compared values differed by tenths of a percent, indirectly confirming that Eq. (12) can be used to describe similar processes.

Figures 1a, 1b present data [1] processed using Eqs. (14) and (15). The linear kinetics equations for $\text{KAlSiO}_4 \cdot \text{H}_2\text{O}$ were obtained at different sorption temperatures (Fig. 1a): $y = 3.75025 + 0.05457x$ (20°C); $y = 3.71485 + 0.06689x$ (40°C); $y = 3.66516 + 0.20492x$ (70°C). From these equations, we determined the values of k for the corresponding temperatures: 68.7 , 55.6 , and 17.9 min^{-1} . Linear equations were obtained for $\text{KAlSi}_5\text{O}_{12} \cdot 2.7\text{H}_2\text{O}$ (Fig. 1b): $y = 3.5156 + 0.14167x$ (20°C), $y = 3.4721 + 0.06263x$ (40°C), and $y = 3.47142 + 0.07795x$ (70°C). The values of constant k were 24.8 , 55.4 , and 44.5 min^{-1} at 20 , 40 , and 70°C , respectively.

Both high sorption capacities and high rates of sorption were typical of nanostructured aluminosilicates. Within several seconds ($t = 1/k$), the sorption capacity reached a value of $1/2A_m$. The energy of activation for the sorption process was calculated from the constant k values at different temperatures, according to the Arrhenius equation. It did not exceed 30 kJ mol^{-1} .

The authors of [2, 3] provided experimental data on the kinetics of the extraction of Co^{2+} , Ni^{2+} , and Cd^{2+} ions by a sorbent fabricated from rice processing byproducts. Analytical dependence (12) was introduced to analyze the kinetic data, except the degree of extraction (α) was used instead of sorption capacities A_m and A_t . The values of constant k (min^{-1}) and the calculated values of the degree of extraction (Δ , %) are shown in Table 2. The maximum degree of extraction (α_m) for each element at the selected temperatures were accepted as equivalent to those obtained for a 180 min duration of sorption. The calculated times needed to reach degree of extraction $0.5\alpha_m$ at 20 , 40 , and 60°C were 16.6 , 9.5 , and 3.7 min for cobalt; 11.4 , 7 , and 6 min for nickel; and 0.2 , 0.06 , and 0.06 min for cadmium, respectively. It was assumed that the substantial differences in the k values for nickel, cobalt, and cadmium were associated with the mechanism of ion extraction, while with cadmium ions it was presumably due to processes of hydrolysis.

The calculated and experimental degrees of extraction for heavy-metal ions (Table 2) differed by no more than several percent. The proposed kinetics equation describes the sorption process for this type of sorbent over a long period of time.

Alosmanov [4] provided data on the kinetics of sorption of cobalt and nickel ions by a phosphorous-containing cation exchanger from aqueous solutions with the concentration of $C_{\text{Me(II)}} = 2 \text{ mmol/dm}^3$ at $t = 22 \pm 2^\circ\text{C}$ and $\text{pH } 6$, $V/g = 0.3 \text{ L/g}$. After 300 min of sorption under quasi-equilibrium conditions, the sorption capacity of the investigated sorbent toward Ni^{2+} ions was 0.448 . It was 0.488 mmol/g toward Co^{2+} ions, and these values were taken as A_m . The value of k (for Eq. (12)) was calculated from the provided data. It was 0.115 min^{-1} for the sorption of nickel, and 0.09 min^{-1} for cobalt. The experimental and calculated values of sorption capacity according to Eq. (12) with parameters $A_m = 0.448 \text{ mmol/g}$ and $k = 0.115 \text{ min}^{-1}$ for nickel, and $A_m = 0.488 \text{ mmol/g}$ and $k = 0.09 \text{ min}^{-1}$ for cobalt, are presented in Table 3. The sorption capacities calculated according to Eq. (12) for the period 0 – 300 min differed from the experimental values by tenths of a percent to 17% (Table 3).

Figure 2 shows the dependences of $1/A_t$ on $1/t$ (kinetics data, Table 3) according to Eq. (14), which are described by linear equations. For the sorption of nickel, $y = 2.06935 + 19.99202x$ (correlation coeffi-

Table 2. Effect of temperature and duration of sorption on the degree of extraction (α , %) of Co^{2+} , Ni^{2+} , and Cd^{2+} ions by the phytic sorbent [2, 3], $(K, \text{min}^{-1})^n$, where $n = 1, 2$, and 3 corresponds to Co^{2+} , Ni^{2+} , and Cd^{2+} , respectively

$T, ^\circ\text{C}$ $(K, \text{min}^{-1})^n$	t, min	Co^{2+}			Ni^{2+}			Cd^{2+}		
		$\alpha, \text{exp.}$	$\Delta, \%$	$\alpha, \text{cal.}$	$\alpha, \text{exp.}$	$\Delta, \%$	$\alpha, \text{cal.}$	$\alpha, \text{exp.}$	$\Delta, \%$	$\alpha, \text{cal.}$
20^3	30	44.7	-1.80	43.9	32.3	18.86	39.81	97.2	1.249	98.43
$(0.06)^1$	60	52.6	1.68	53.5	39.8	13.7	46.16	98.9	-0.14	98.76
$(0.088)^2$	120	60.5	0	60.05	52.4	-4.8	50.15	99.1	-0.17	98.93
$(4.97)^3$	180	68.4	-0.9	67.77	54.9	0.07	54.86	99.1	-0.12	98.98
40	30	60.5	-0.01	60.49	47.4	-0.08	47.36	99.2	0	99.20
$(0.105)^1$	60	71.1	-3.37	68.78	57.4	0.09	52.30	99.3	0	99.30
$(0.143)^2$	120	71.6	3.02	73.83	57.4	-4.0	55.18	99.4	-0.06	99.34
$(16.55)^3$	180	79.7	5.2	75.69	58.4	-3.8	56.21	99.2	0.16	99.36
60	30	86.8	-45	83.06	67.4	-0.029	67.38	99.2	0	99.20
$(0.268)^1$	60	80.0	9.0	87.93	52.4	28.76	73.56	99.3	0	99.30
$(0.165)^2$	120	93.4	-3.1	90.58	67.4	12.58	77.10	99.3	0.04	99.4
$(16.55)^3$	180	92.1	0.6	91.50	81.0	-3.37	78.36	99.4	-0.04	99.36

Table 3. Experimental and calculated values of the sorption capacity (mmol/g) of phosphorous-containing cationite toward nickel and cobalt ions [4]

No.	t, min	Ni(II)			Co(II)		
		$\Delta, \%$	$A_t(\text{exp.})$	$A_t(\text{cal.})$	$\Delta, \%$	$A_t(\text{exp.})$	$A_t(\text{cal.})$
1	10	0.4	0.240	0.239	3.8	0.240	0.231
2	20	7.6	0.336	0.312	2.7	0.4	0.313
3	30	8.3	0.376	0.347	17.9	0.420	0.356
4	40	10	0.408	0.368	14.3	0.440	0.382
5	60	7.4	0.420	0.391	12.8	0.464	0.411
6	70	7.5	0.428	0.398	12.1	0.472	0.421
7	90	7.8	0.440	0.408	10.5	0.480	0.434
8	110	7.9	0.448	0.415	10.1	0.488	0.443
9	150	5.9	0.448	0.423	7.4	0.488	0.454
10	200	4.4	0.448	0.429	5.6	0.488	0.462
11	250	3.7	0.448	0.432	3.6	0.488	0.471
12	300	3.7	0.448	0.432	3.8	0.488	0.470

cient $R^2 = 0.98058$); for the sorption of cobalt, $y = 1.84865 + 20.66961x$ (correlation coefficient $R^2 = 0.9189$).

According to Eq. (15), the values of k (min^{-1}) were 0.103 for nickel and 0.089 for cobalt. Within a measuring error of several percent, the same constant values were obtained by processing the experimental data according to Eq. (13). The results show that the mechanism behind the sorption of nickel and cobalt ions by phosphorous-containing cation-exchangers [4] prepared according to [7, 8] throughout the period of time was due to cation exchange and described by kinetics equation (12) derived by analyzing the

topochemical reaction between the sorbate and sorbent.

Using barium silicate $\text{BaSiO}_3 \cdot 2.3\text{H}_2\text{O}$ synthesized in the multicomponent system $\text{BaCl}_2 \cdot 2\text{H}_2\text{O} - \text{KOH} - \text{SiO}_2 - \text{H}_2\text{O}$, the authors of [9] obtained data on the kinetics of extracting Sr^{2+} and Ca^{2+} ions (Table 4) from solutions simulating the waters of holding basin No. 11 of PA Mayak (composition of the holding basin waters [9], mg/L: Sr^{2+} , 10–12; Ca^{2+} , 100; Mg^{2+} , 75; Na^+ , 132; K^+ , 15; Cl^- , 82; SO_4^{2-} , 650; pH 7.6) at the ratio $S : L = 1 : 40$ and 20°C . Barium silicate was synthesized at 90°C from aqueous solutions of potassium silicate (potassium liquid glass with barium chloride and a sil-

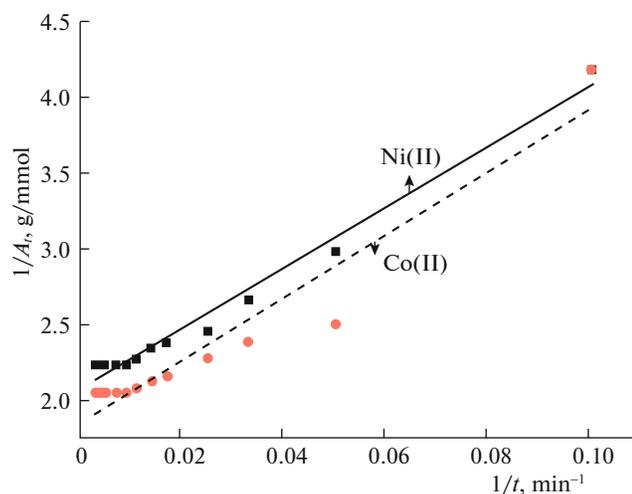


Fig. 2. (Color online) Dependences of the inverse sorption capacity of phosphorous-containing cation exchanger $1/A_t$ toward Ni^{2+} and Co^{2+} ions from $1/t$ [4].

icate module of 1). The sample of barium silicate was fabricated from powder consisting of nanodispersed spherical particles of virtually equal sizes with diameters no larger than 50 nm, which formed conglomerates consisting of nanoparticles (Fig. 3).

Using the experimental values of α_t over time (Table 4) and under the condition that $\alpha_m = 94.8$ upon the sorption of Sr^{2+} ions and $\alpha_m = 88.9$ upon the sorption of Ca^{2+} ions, the values of k were calculated according to Eq. (13). They were 140 h^{-1} for the sorption of strontium and 25 h^{-1} for the sorption of calcium. The calculated values (according to Eq. (12)) of α_t and the difference (Δ , %) between the experimental and calculated values of α_t (which did not exceed several percent) are given in parentheses in Table 4. The maximum deviations of 5% upon the sorption of strontium over 0.666 h and 8.45% upon the sorption of calcium over 0.333 h must be considered measuring errors. The data on kinetics (Table 4) were processed according to Eqs. (14), (15) and are shown in Fig. 4. The maximum degree of decontamination with respect to Sr^{2+} ions (96.69%) and the value $k = 130.3 \text{ h}^{-1}$ (also

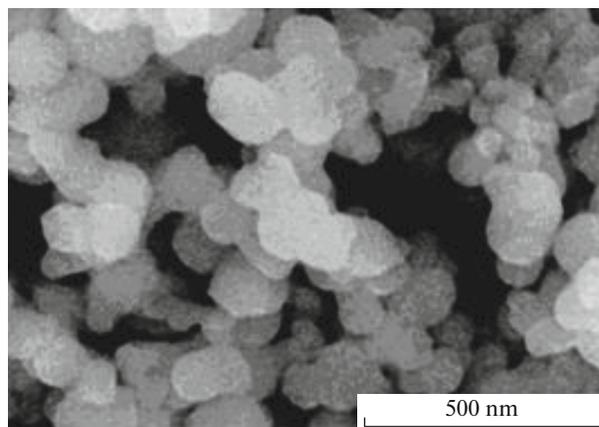


Fig. 3. Morphology of microparticles of the sample of barium silicate $\text{BaSiO}_3 \cdot 2.3\text{H}_2\text{O}$, examined on a high-resolution Hitachi S5500 (Japan) scanning electron microscope.

obtained according to Eq. (13)) were calculated with linear equation $y = 0.01045 + 0.0000791x$ (correlation coefficient $R^2 = 0.88031$) and allowing for Eqs. (14) and (15). With respect to Ca^{2+} ions, $y = 0.01106 + 0.000457x$ (correlation coefficient $R^2 = 0.88031$). The maximum degree of decontamination was 90.4%, and $k = 24.2 \text{ h}^{-1}$.

In extracting Sr^{2+} ions from aqueous solutions of complex ionic compositions (simulating the waters of holding basin No. 11 of PA Mayak, or so-called Techa river waters), the synthesized nanostructured barium silicate had a time of reaching a sorption capacity that was half the maximum value at the ratio $S : L = 1 : 40$ (or half the degree of decontamination) no longer than 30 s. This material must therefore be considered a promising sorbent for the decontamination of liquid radioactive waste under static sorption conditions.

The authors of [5] studied the capacity of static sorption toward Cs^+ ions for composite sorbent KS-2, which was 90% aluminosilicate (the aluminosilicate composition was not given) and 10% polyacrylamide upon the sorption of Cs^+ ions from aqueous solutions with Cs^+ ion concentrations of 0.1 to 5.0 mEq/L ($S : L = 1 : 50$; temperature, 20°C ; duration of sorption, 24 h). It was established that the maximum sorption capacity was $0.065 \pm 0.012 \text{ mEq/L}$, and the time needed to reach

Table 4. Degrees of extraction of Sr^{2+} and Ca^{2+} ions by nanodispersed barium silicate $\text{BaSiO}_3 \cdot 2.3\text{H}_2\text{O}$

t , h	0.083	0.333	0.5	0.666	1	1.5
α_t	87.5	92.2	96.2	94.3	94.3	94.8
α_t , % (Sr)	(87.28)	(92.80)	(93.46)	(93.79)	(94.12)	(94.35)
Δ , %	0.24	-0.6	1.3	-5.0	1.72	0.47
α_t	59.7	86.7	81.4	84.0	83.3	88.9
α_t , % (Ca)	(59.98)	(79.36)	(82.31)	(83.86)	(85.48)	(86.59)
Δ , %	-0.48	8.45	-1.1	0.16	-2.6	2.59

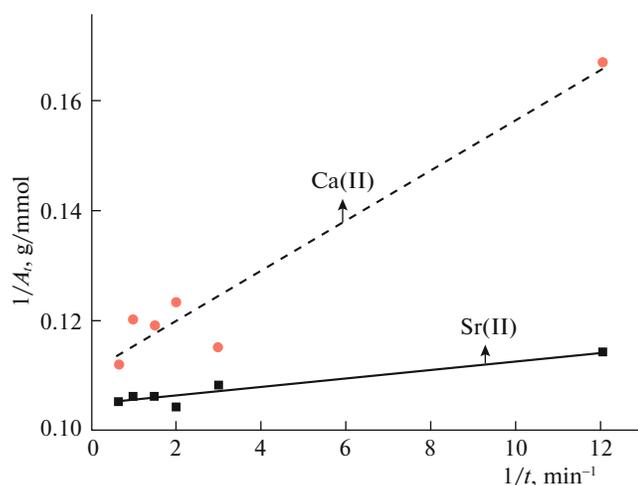


Fig. 4. (Color online) Dependence of the inverse value of nanostructured barium silicate extracting strontium and calcium ions from a solution.

the equilibrium concentration of the sorbate in the solution was ~ 80 min. The experimental data on kinetics were processed according to Eqs. (14) and (15), yielding sorption equation $y = 0.00813 + 0.12221x$ with coefficient of correlation $R^2 = 0.9929$ and constant $k = 0.066 \text{ min}^{-1}$. In other words, the time needed to reach half the maximum value of sorption (50%) was no more than 15–20 min, according to the proposed equation.

CONCLUSIONS

An equation for the kinetics of the topochemical process of sorption was obtained, based on an analysis using the law of mass action. The proposed equation was used to describe the kinetics of known topochemical reactions. It was proven experimentally that this equation describes with high precision the data on kinetics of sorption of heavy-metal ions by different synthetic sorbents, including ones based on aluminosilicates with different ratios of silicon to aluminum. The equation was used to analyze data on the kinetics of sorption of heavy-metal ions from aqueous solu-

tions of different ionic compositions by a sorbent based on a derivative of inositol hexaphosphoric acid, phosphorous-containing cation exchangers, and a composite sorbent consisting of aluminosilicate and polyacrylamide.

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