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Mathematical modelling of regeneration the filtering media bed of granular filters

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ABSTRACT

The work of predominant majority of filters in technological schemes of water treatment is based on alternation of two processes, filtering and washing. The presence of multi-component impurities in washing waters has a negative impact on the processes of their treatment and leads to a significant deterioration of the waste effluent quality. The solution of the problem is achieved by separating the contamination of washing water at a phase-dispersed state reducing the concentration of ferruginous compounds and bringing their concentration in washing waters to a level that is acceptable to discharging into waste water treatment facilities or reservoirs. Developed a mathematical model of the process of the liquid treating from multi-component contaminations, which takes into account the interaction of hydrodynamic parameters, change of hydraulic properties of the medium, initial and boundary conditions of modelling problem of the beds regeneration taking into account the appropriate values of the concentrations of contamination in the liquid and deposit, the reverse effect on the filtration components, in particular, to the porosity and the coefficient of the separated deposit particles. Determined the time of the protective action of the filter media bed and the time of its regeneration, taking into account the values of the concentrations of contaminations in the water submitted for purification, the filters media bed height and the speed of the washing water movement.

1. INTRODUCTION

The state of water resources and water supply of the population of any country remains one of the main actual threats to national security in the environmental sphere. In modern society, rational use of water resources, in the conditions of water shortage, deterioration of its quality is a complex scientific and technical problem [1-3].

An important place in the field of water supply takes the process of water preparation. In recent years, the purification of natural water, improvement of water preparation technologies and development of new effective resource-saving methods becomes more and more actual [4-5].

The main sources of water supply are surface and groundwater. Surface water is mostly contaminated with pesticides, petroleum products, heavy metal salts, phenols, biogenic substances, etc., removing them from water is a complicated and costly process [6]. Therefore, the preference is given to underground waters if it's possible [7]. Groundwater is better protected from contaminators; therefore, in many countries of the world it is the main source of economically-drinking water supply. For example, in Italy they account for 93% of the total water consumption from water sources, 95% in Lithuania, 91% in Germany, 70% in Switzerland, 45% in Russia and only 25% in Ukraine [4]. More than 50% of groundwater in Ukraine has high levels of iron, especially in the central and western regions [1, 7].

Various technological schemes are used for water purification taking into account the characteristics of contaminating elements, consumers' demands for water quality, wastewater treatment plants productivity, etc. [2, 4-5].

The choice of the method of water preparation is carried out on the basis of the study of water quality indicators of the water source (chemical composition of water) obtained as a result of physicochemical, sanitary-bacteriological and technological analyzes and a number of other indicators [1]. The main place in such methods is occupied by filtering constructions [4] the efficiency of their work depends not only on the quality of purified water, but also on the cost of water purification [2, 5]. The work of the vast majority of filters in the technological schemes of water purification is based on the alternation of two processes, filtering and washing [7]. The deterioration of the water quality after the filter or the achievement of marginal head losses in the filter media bed indicates the need to withdraw the filter for washing [8]. Certainly, the granulated media bed of fast filters is recovering by a reverse flow of water [9]. Contaminations, that are washed out from the filtering media bed are enough mineralized and concentrated. The content of ferrous compounds amounts hundreds of g/m^3 [1].

The effect of water purification to the filters combines the processes of detaching the colloidal and suspended particles in the grains of the filtering bed, the processes of separation of previously adherent particles and their removal by a stream of washing water. After the maximum saturation of contaminations, the filtering media ceases to purify water effectively [1, 4, 9]. The rinsing of the filtering media of the water purifying filters (regeneration) takes place in the extended state with intense flow of water in the opposite direction to the filter vector. Depending on the type of filtering bed classify such methods of filters regeneration as water filters, pulsating filters, water-surface filters, water uninterrupted filters, water-air washing filters [7]. Each of the regeneration methods can be used depending on the quality of the supplied water for purification, properties of filtering bed, the size and productivity of the filters, the degree of filtering media contamination, etc. [1].

One of the most urgent tasks that require the constant attention is to reduce the concentration of ferruginous compounds and to prove their concentration in the washing waters to a level that is permissible to discharge into wastewater treatment systems or water reservoirs. The purification of washing waters is complicated due to their significant multi-component and diffraction [10]. The presence of multi-component impurities in washing waters, negatively affects to the processes of their purification. This leads to a significant deterioration of the effluent quality [11]. Problem remains the question of the separation of contaminants by phase-dispersed state and type of substances in the washing water.

In the Directive "About Purification of Wastewater in Cities" No. 91/271 / ЄEC a number of environmental protection measures are presented. In Irish quite serious about environmental protection problems due to lower concentration in water washing [12].

To reduce the burden for the environment and reduce the cost of operating water treatment plants, it is expedient to use mathematical modelling of regeneration the media of the filters.

Therefore, the main purpose of the work is the development of a mathematical model for regeneration of granular filters media, which takes into account the interaction of hydrodynamic parameters, the change in the hydraulic properties of the medium, the initial and boundary conditions of the modelling problem of filters media bed regeneration, taking into account the concentrations of contamination in the liquid and deposit.

2. MATERIALS AND METHODS

There are two types of liquids' movement in a porous medium, laminar and turbulent. The majority of the researchers [13-19] were engaged in the problem of the laminar flow of water in the porous medium, using methods of idealizing the process to simplify the calculations.

During the filtering in turbulent mode there is no exact correlation between the rate of filtration and the hydraulic displacement. Therefore, there are many dependencies [7, 17, 20] proposed by various authors, which were obtained empirically using the methods of the theory of similarity and dimensions. The criteria by which the filtration flow regime is determined is the Reynolds number and the resistance coefficient [1, 13, 18].

The Reynolds number depends on the following basic parameters as the rate of filtration, the typical particles parameter, the coefficient of porosity [7]. The coefficient of resistance is influenced by such main parameters as the typical particles parameter, the pressure drop across the length of the filtering column, the coefficient of porosity [4, 7, 9, 10]. An important factor for determining the properties of a filtering stream through a porous medium is given to such an indicator as the coefficient of grain form, which is determined on the basis of experimental researches [1, 17]:

$$\alpha = \frac{d \cdot m}{1-m}\sqrt{\frac{5.35m \cdot i}{v \cdot \mu}}\ , \tag{1}$$

where i – hydraulic slope.

Taking into account the coefficient of grains form using the theory of similarity and dimensions, D.M. Minz and S.A. Schubert [8] proposed the following formulas for determining the Reynolds number and the resistance coefficient:

$$\mathrm{Re} = \frac{v \cdot d_{eq} \cdot \rho_1}{6\mu \cdot \alpha \cdot (1-m)}, \tag{2}$$

$$\eta = \frac{P \cdot m^3 \cdot d_{eq}}{L \cdot \rho_1 \cdot v^2 \cdot 6\alpha(1-m)}, \tag{3}$$

where, v – filtration rate, cm/s; d_{eq} – equivalent diameter of the grains, cm, ρ_1 – density of the liquid, g/cm^3, $\frac{P}{L}$ – pressure drop, which refers to the unit thickness of filtering media.

Mathematical models of water and water-air treating of fast filters differ from the known mathematical models of filtering processes [7]. At the same time, it is clear that during water washing, the mathematical tasks of filtration and regeneration must coincide with the accuracy of the coefficients and additional conditions.

According to [17], the efficiency of regeneration (washing) of heavy bed can be estimated by such expressions:

$$\mathrm{E} = f(d_{eq}, \mathrm{T}, L_0, \frac{\rho_{gr} - \rho_w}{\rho_{gr}} g, V, \mu, t), \tag{4}$$

where, ρ_{gr}, ρ_w – density of grains of filtering bed and water, kg/m^3, d_{eq} – the equivalent diameter of the filtering bed, m, m – bed porosity, μ – kinematic coefficient of viscosity of washing water, m^2/s, g – acceleration of free fall, m^2/s, V – washing water velocity, m/h, L_0 – bed height, m, t – washing time, s.

Using the Relay method and combining the parameters, all these dimensional values can be described by the function:

$$\mathrm{E} = \mathrm{E}(\mathrm{Re}, Ar, \bar{t}, \mathrm{T}, L_0/d_{eq}), \tag{5}$$

where, $\mathrm{Re} = V \cdot d_{eq}/\mu$ – the Reynolds number [7, 8].

Expression (4) for buoyant bed are adjusted in the Archimedes number, where accepted

$(\rho_w - \rho_{gr})$, but not $(\rho_{gr} - \rho_w)$.

$$\mathbb{A}r = g(\rho_w - \rho_{gr}) \cdot d^3_{eq}/\rho_w \mu^2\ , \tag{6}$$

where Ar – the Archimedes number; $\bar{t} = V \cdot t / L_0$ – the Struchals number (homochronity criterion) [18].

Based on experimental studies suggested a significant number of dependencies on washing as heavy (sand, stone, anthracite, etc.) [9, 10, 15-18, 19-23] and buoyant bed (polystyrene) [1, 17]. However, such dependencies can be used in limited conditions for preliminary selection of constructive parameters of filters and have low prognostic value.

A large number of equations were proposed to describe the kinetics of the process of bed regeneration, which can be divided into linear and nonlinear ones, which take into account the separation of previously adhered particles and are inseparable [18, 23].

In the theory of filtering of low-concentration suspensions, it is accepted to consider two main parameters, according to which the filter can be output for washing, time to achieve the ultimate pressure loss and time of the bed protective action [1, 4, 7-10, 13-15, 17].

The duration of the protective action of the filtering bed is the time during which the filtering bed can clarify the water to the specified quality. For heavy bed [8] the duration of protective action is determined by the formula:

$$\tau_{pr} = \frac{1}{K}\left[\frac{h}{v^{1,7} \cdot d^{0,7}} - \frac{S_0 \cdot d}{v}\right], \qquad (7)$$

where, K – parameter obtained according to experimental results, h – the thickness of the filtering bed, S_0 – a constant that depends on the given ratio of turbidity of the water entering to the treating C_0, to the turbidity of the filtrate C_f.

Possible the variant, when the filter is not outputs for washing not because of the deterioration of the quality of the filtrate, but because of achievement the boundary pressure losses. In this case the duration of the filter cycle for heavy bed can be determined by the formula [7]:

$$\tau_b = \frac{H_b - H_0}{H_0 \cdot f(A)} \cdot \frac{b}{a} x, \qquad (8)$$

where, H_b, H_0 – boundary and initial pressure loss in the filter, x – thickness of the filtering media bed.

Improvement of mathematical models regeneration of filters bed should be based on the consideration of the interaction of hydraulic and physicochemical processes during water filtration, changes the hydraulic properties of the medium, nonstationaryty of the clarification process, the duration of the filter operation, the specificity of the kinetics of mass exchange, peculiarities of the influence of the formed medium properties, etc. [9].

The following problems are solved in the article:

- the development of a mathematical model for the bed regeneration of a granular fast filter, which takes into account the interaction of hydrodynamic parameters, the change in the hydraulic properties of the medium, the initial and boundary conditions of the modelling problem of the bed regeneration, taking into account the appropriate values of concentration of contamination in the liquid and deposit;
- establishing the time of the protective action of the filters bed τ_{pr} and the time of its regeneration τ_b, taking into account the values of the concentrations of contaminants in water, that comes for purification;
- researching the efficiency of water purification on a granular filter, taking into account optimized parameters according to the results of the study;
- determining the duration of bed regeneration time depending on the height of the filters bed $L_0(v_p, v_f)$ and the washing water velocity v_p.

3. RESULTS AND DISCUSSION

Depending on the characteristics of the captured contaminants and the structure of the filtration material, the significant amounts of clean water can be used, that is the reason for increase in the cost of treated water.

At present, the most commonly used method of regenerating of the granular bed it's washing it in the direction of opposite filtration [17, 18, 23].

The theory of various types of bed regeneration is based on simplified mathematical models that don't take into account all the parameters of the process of washing or have empirical character [8].

Based on the above mentioned, let's consider the following problem which describes the process of 'filtering-regeneration' in the complex [10]:

$$\begin{cases} D\dfrac{\partial^2 c}{\partial x^2} - \sigma\dfrac{\partial c}{\partial t} - v_i\dfrac{\partial c}{\partial x} = \dfrac{\partial \rho}{\partial t}, \\ \dfrac{\partial \rho}{\partial t} = \beta_i c - \alpha_i \rho, \end{cases} \qquad (9)$$

$$c|_{x=0} = c_*(t),\ c|_{t=0} = c^*(x),\ \rho|_{x=0} = \rho_*(t),\ \rho|_{t=0} = \rho^*(x), \qquad (10)$$

where, $c_*(t) = c_* = const$, $c^*(x) = 0$, $\rho_*(t) = \rho^*(x) = 0$ at the case of filtering, $0 < x < \infty$, $0 < t < \infty$, τ_{pr} – time of the protective action of the filter, $\beta_i = const$ – coefficient characterizing the volumes of captured impurity particles per unit time, $a_i = av_i$ ($a = const$) – coefficient characterizing the volumes of detached particles at the same time, $v_i = const$ – filtering rate ($v_i = v_f$) or regeneration ($v_i = v_p$); at the same time in the case of regeneration, the direction of the filtering rate changes to the opposite, the initial and boundary conditions of the modelling problem are given taking into account the corresponding values the concentrations of contamination in the liquid and in the deposit, respectively, the time of the protective action of the filter $t = \tau_{pr}$ and at $x = L, x = 0$ ($c|_{x=L} = \mu_p c_*$, $c|_{t=\tau_{pr}} = c(x, \tau_{pr})$, ($\mu_p = const << 1$), $\rho|_{t=\tau_{pr}} = \rho|_{x=L} = \rho(L, \tau_{pr})$).

We assume that the bed regeneration is carried out in the direction opposite to the filtering (counter flow), but under the same laws, then the requirements of the effective operation of the filter can be showed as

$$p = \frac{q - q_p}{q} = 1 - \frac{v_p \tau_p}{v_f \tau_{pr}} \geq p_*, \qquad (11)$$

where, $q = v_f \tau_{pr}$ – volume of filtrate obtained during the protective action of the filter τ_{pr}, $q_p = v_p \tau_p$ – the amount of filtrate used to the bed regeneration, τ_p – the time of bed regeneration, p_* – minimum permissible efficiency of filters work.

The time of the protective action of the filter τ_{pr} and the regeneration time τ_p are the result of solving equations:

$$\mu = c(L,\tau_3) = c_0(L,\tau_3) + \sum_{i=1}^{n} \varepsilon^i c_i(L,\tau_3) + R_c(L,\tau_3,\varepsilon), \quad (12)$$

$$\psi = \rho(L,\tau_p) = \rho_0(L,\tau_p) + \sum_{i=1}^{n} \varepsilon^i \rho_i(L,\tau_p) + R_\rho(L,\tau_p,\varepsilon), \quad (13)$$

where, μ – the critical value of the contaminations concentration at the outlet of the filter, $C(x,t)$ – solution of "direct" problem (filtering); ψ – a coefficient characterizing the maximum allowable norm of deposit in the filter, $P(x,t)$ – solution of "reverse" task (regeneration):

$$c_0(x,t) = e^{-\frac{\beta x}{v} - \alpha t}\left(c_*(0) I_0\left(2\sqrt{\frac{\alpha\beta}{v} xt}\right) + \right.$$
$$+ \frac{\alpha}{v}\int_0^x I_0\left(2\sqrt{\frac{\alpha\beta}{v}(x-\xi)t}\right)\rho_*(\xi) e^{\frac{\beta\xi}{v}} d\xi +$$
$$\left. + \int_0^t e^{\alpha\eta} I_0\left(2\sqrt{\frac{\alpha\beta}{v} x(t-\eta)}\right)\left[\frac{dc_*(\eta)}{d\eta} + \alpha c_*(\eta)\right] d\eta \right),$$

$$\rho_0(x,t) = e^{-\frac{\beta x}{v} - \alpha t}\left(\rho_*(0) I_0\left(2\sqrt{\frac{\alpha\beta}{v} xt}\right) + \right.$$
$$+ \frac{\beta}{v}\int_0^t e^{\alpha\eta} I_0\left(2\sqrt{\frac{\alpha\beta x}{v}(t-\eta)}\right) c_*(\eta) d\eta +$$
$$\left. + \int_0^x e^{\frac{\beta\xi}{v}} I_0\left(2\sqrt{\frac{\alpha\beta t}{v}(x-\xi)}\right)\left[\frac{d\rho_*(\xi)}{d\xi} + \frac{\beta}{v}\rho_*(\xi)\right] d\xi \right),$$

$$c_i(x,t) = \frac{e^{-\frac{\beta x}{v} - \alpha t}}{vb}\int_0^x\int_0^t e^{\frac{\beta\xi}{v} + \alpha\eta} \mathrm{I}_0\left(2\sqrt{\frac{\alpha\beta}{v}(x-\xi)(t-\eta)}\right) \times$$
$$\times\left(\frac{\partial^3 c_{i-1}(\xi,\eta)}{\partial\xi^2\partial\eta} + \alpha\frac{\partial^2 c_{i-1}(\xi,\eta)}{\partial\xi^2} - \frac{\partial^3 \rho_{i-1}(\xi,\eta)}{\partial\xi^2\partial\eta}\right) d\eta\, d\xi, \quad (14)$$

$$\rho_i(x,t) = e^{-\frac{\beta x}{v} - \alpha t}\int_0^x\int_0^t e^{\frac{\beta\xi}{v} + \alpha\eta} I_0\left(2\sqrt{\frac{\alpha\beta}{v}(x-\xi)(t-\eta)}\right) \times$$
$$\times\left(\frac{\partial^3 \rho_{i-1}(\xi,\eta)}{\partial\xi^3} + \frac{\beta}{v}\frac{\partial^2 c_{i-1}(\xi,\eta)}{\partial\xi^2}\right) d\eta\, d\xi,$$

$$c_i(x,t) = \frac{e^{-\frac{\beta x}{v} - \alpha t}}{vb}\int_0^x\int_0^t e^{\frac{\beta\xi}{v} + \alpha\eta} \mathrm{I}_0\left(2\sqrt{\frac{\alpha\beta}{v}(x-\xi)(t-\eta)}\right) \times$$
$$\times\left(\frac{\partial^3 c_{i-1}(\xi,\eta)}{\partial\xi^2\partial\eta} + \alpha\frac{\partial^2 c_{i-1}(\xi,\eta)}{\partial\xi^2} - \frac{\partial^3 \rho_{i-1}(\xi,\eta)}{\partial\xi^2\partial\eta}\right) d\eta\, d\xi,$$

$$\rho_i(x,t) = e^{-\frac{\beta x}{v} - \alpha t}\int_0^x\int_0^t e^{\frac{\beta\xi}{v} + \alpha\eta} I_0\left(2\sqrt{\frac{\alpha\beta}{v}(x-\xi)(t-\eta)}\right) \times$$
$$\times\left(\frac{\partial^3 \rho_{i-1}(\xi,\eta)}{\partial\xi^3} + \frac{\beta}{v}\frac{\partial^2 c_{i-1}(\xi,\eta)}{\partial\xi^2}\right) d\eta\, d\xi,$$

where, I_0 – Bessel functions of the first kind of zero order from an imaginary argument.

Demanding the sufficient smoothness of the initial and boundary conditions and the coefficients of the system of equations (9)-(10) (the existence of uninterrupted derivatives to the fourth order inclusive) and their consistency at the point $x = L$ on the basis of the maximum principle we get at the validity of such a statement

$$R_c(x,t,\varepsilon) = O(\varepsilon^{n+1}), \; R_\rho(x,t,\varepsilon) = O(\varepsilon^{n+1}). \quad (15)$$

The protective action time of the filter τ_{pr} is determined by formula (12) as the time during which the concentration at the filter outlet $c(L,\tau_{pr})$ reaches the level $\mu = 0,05$. It is also assumed that the bed regeneration process is carried out by filtrate with concentration μ_p, i.e. by filtrate collected at time τ_{pr} in some capacity, where it mixes completely. Time of regeneration τ_p was determined by formula (13) as the time during which the maximum relative density of bed saturation by precipitate $\rho(x,\tau_p)$ decreases to the level $\psi = 0,05$.

Results of numerical calculations at $v_f = 10$ m/h are shown in Figure 1-3.

Based on the results presented in Figure 1 we see that dependence τ_{pr} from L approximates to the linear (Shilov equation), and dependence τ_p from L can be approximated by a straight line starting from some L_0. This will substantially simplify the practical calculations in cases where the coefficients k and b, which determine the position of the straight line $\tau_p = kL + b$,which are predefined using the calculation program τ_p and τ_{pr} by formulas (12), (13). At sufficiently high regeneration rates, at v_p ~2,8 m/s (curve 5) time of filters regeneration with bed height $L > L_0$ can be assumed to be approximately constant, independent of L. It is also necessary to indicate that the regeneration time τ_p exists only starting from some τ'_p, at which ρ reaches the level ($\rho(L,\tau'_p) = \psi$).

The nature of the dependence of the concentration of the filtrate used for regeneration, from L shown in Figure 2

The curves shown in Figure 3 illustrate the ratio of the utility part of the received filtrate to its total volume depends on the bed height L. And also, they show that with relatively small ones L there are possible cases when for the regenerating of the bed we need much more filtrate than it was obtained during the process of filtration. With the increase L ratio p approximate to one. Therefore, the limit on the amount of filtrate consumed for bed regeneration $\left(p_0 \le \left(1 - \frac{q_p}{q}\right) \le 1\right)$, equivalent to a restriction on its height L.

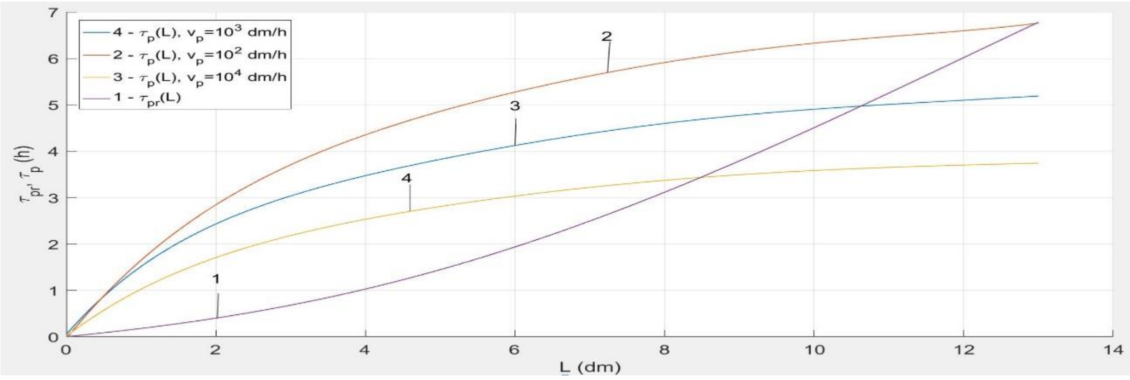

Figure 1. Dependence τ_{pr} and τ_p from: (1) – $\tau_{pr}(L)$, (2 – 5) – $\tau_p(L)$, respectively, at $v_p = 10^2, 10^3, 10^4$ dm/h

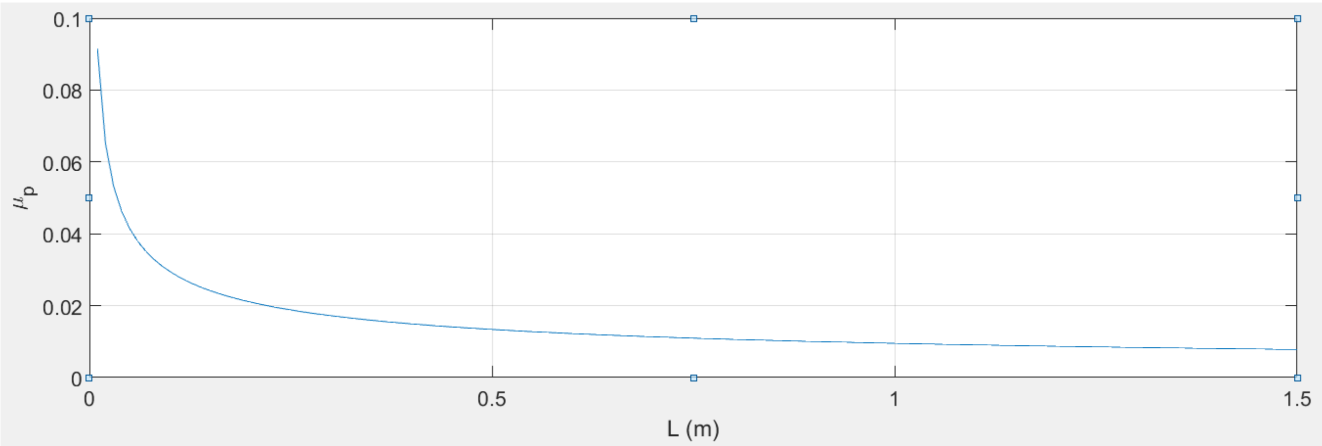

Figure 2. Dependence of the concentration of contaminating substance in filtrate μ_p from the bed height L

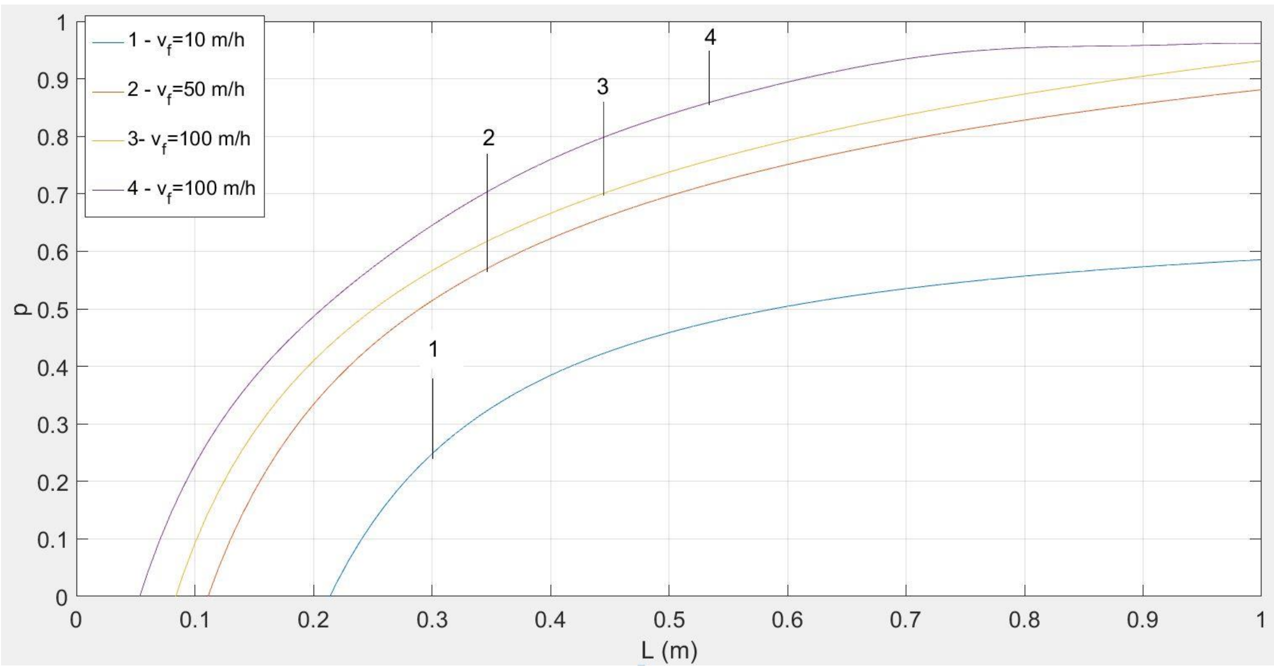

Figure 3. Dependence of the filter efficiency p from the bed height L. Curve (2) – $v_f = 10$, (3) – 50, (4) – 10^2, (5) – 10^3 m/h

Actually, if you want the filter efficiency to be at least some p_0, then the height of its bed should be no less than some $L_{\min}(p_0)$. Area of high efficiency values with relatively small L ($L \sim 3{,}16$) for filtration is not suitable, because the volume of filtrate obtained in this case is small.

Compare the data obtained experimentally and calculated according to the developed model.

Table 1. Results of a natural experiment

Time, sample, s	Washing mode				Bed hight, cm			e,%	V_{samp}, ml	optimal dencity	Fe, mg/l
	W,l	t,s	Q, l/s	I, l/s*m^2	L1, sm	L2, sm	L, sm				
0	1	2,84	0,3	16,9	98,6	102,6	4	4,1	20	0,45	2,29
20	1	3,18	0,31	17,8	98,6	107,6	9	9,1	0,5	0,336	68,38
40	1	2,12	0,47	26,6	98,6	112,7	14,1	14,3	2	0,287	14,60
60	1	2,39	0,42	23,6	98,6	112,1	13,5	13,7	5	0,232	4,72
80	1	2,55	0,39	22,2	98,6	111,5	12,9	13,1	10	0,366	3,72
100	1	2,65	0,38	21,3	98,6	109,5	10,9	11,1	10	0,26	2,65

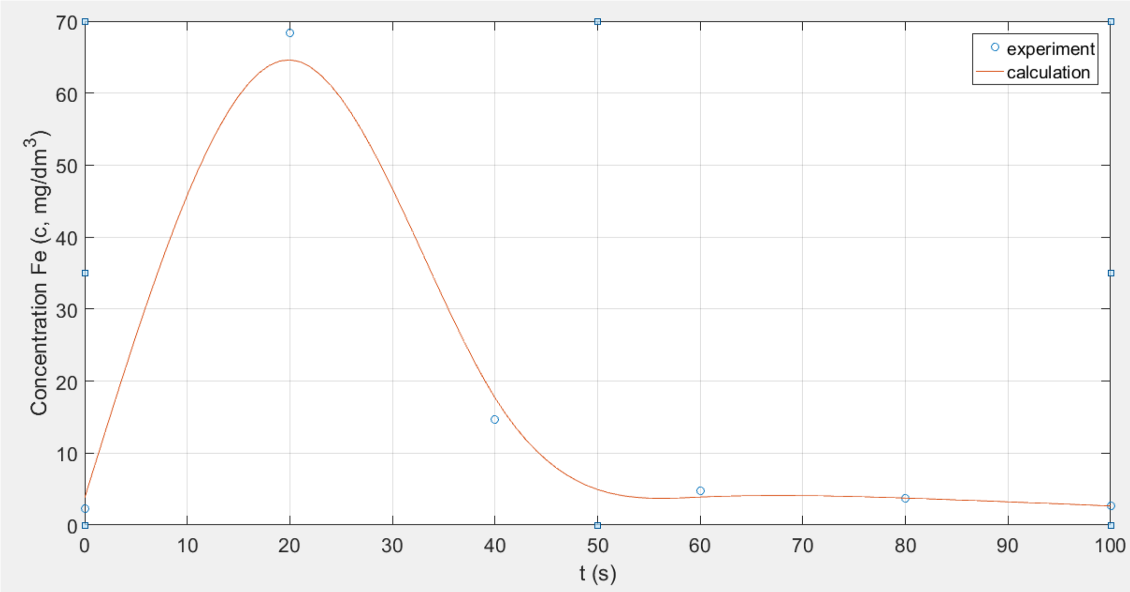

Figure 4. Dependence *Fe* concentration at the outlet of the filter regeneration over time (experimental and calculated)

Consistency of the finding the effectiveness of the filters is based on finding the time of the protective action of the filter τ_{pr} and regeneration time τ_p. By the formula (11) calculate the effectiveness of the filters work. If this value is less than acceptable, then, after changing one or more parameters (regime characteristics), the calculations are repeated until the satisfactory efficiency value is obtained.

Figure 4 shows the dependence of the concentration of iron compounds on the outlet of the filter during the regeneration time, moreover experimental and calculation dependencies mutually agree with each other.

4. CONCLUSIONS

1. Developed the mathematical model of the bed regeneration of a granular fast filter, which takes into account the interaction of the hydrodynamic parameters, the change of the hydraulic properties of the medium, the initial and boundary conditions of the modelling problem of the bed regeneration, taking into account the appropriate values of concentrations of contamination in the liquid and deposit.
2. Established the time of the protective action of the filters bed τ_{pr} and time of its regeneration τ_p, taking into account the values of the concentrations of contaminations in the water which entering for the purification.
3. According to results of the research established efficiency of water purification in the grain filter, taking into account the optimized parameters.
4. Determined the time duration of the bed rdegeneration depending on the height of the filters media bed $L_0(v_p, v_f)$ and the rate of washing water v_p.
5. Comparative characteristic of the data calculated on the basis of the developed mathematical model and data obtained by research are conducted.

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