Functioning of filter structures in changing velocity conditions over time

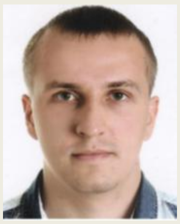
Kravchuk Oleksandr

Kyiv National University of Construction and Architecture
31, Povitroflotsky prosp., Kyiv, Ukraine, 03037
kravchuk.oa2@knuba.edu.ua, orcid.org/0000-0001-6578-8896

Summary. One of the main constructions, which are used for preparing water of necessary quality, is rapid filter. Functioning of such structures, as a rule, takes place in free-flow regime. Structures operation time depends on two main parameters: water treatment quality and provision of necessary calculated discharge. In this case it is accepted that fluid velocity in a filter bed is constant. In fact, functioning of such structures can differ from reviewed ones. A variant of rapid filters operation under substantial variation of filtration velocity was analyzed in the article. Specific operation conditions of such structures and differential equations, which describe water flow in filter medium and intensity of contaminants removal, were reviewed.

As the result of conducted research, variation over time of suspended particles concentration in the filtrate, filter productivity, quantity of not clarified suspension which accumulates over filter bed under various sorption properties of filter medium was shown. Engineering calculation methodology of filtration structures main characteristics, including technological filtration time, filtration cycle duration and optimal filter media height were suggested. Mentioned calculated relations and equations were illustrated by example series with typical initial data.

Key words: filtration, suspension, sediment, filtration cycle, filtrate.



Oleksandr Kravchuk
Postgraduate student of the water supply and water sewerage department

INTRODUCTION

High-quality water delivery for the population and industrial production has always been an important social and technological problem. Thus, the issue of water treatment from different pollution types has been given much attention. The main research directions are how to develop new methods of treatment and improve existing ones [1]. One of the main structures, which are used for that, are rapid filters and other types of filters [2…5], which water delivery is usually carried out under a constant discharge. However, due to insufficient permeability of the filtering material, a layer of water accumulates over its surface in course of time, filtration velocity changes, in which usually takes place at treatment plants with small efficiency. As a result, at the entrance to the filter medium, the increasing head is arisen, which is increasing over time, and is able to significantly accelerate filtration process. On the other hand, under the deposition of suspended solids in the medium pores, which is accompanied by bounding significant water amounts, its hydraulic resistance is increasing, which ultimately leads to an abrupt decrease of the filtering process intensity. In particular, the progressive silting of filter material often limits the operation of water treatment filters [6, 7].

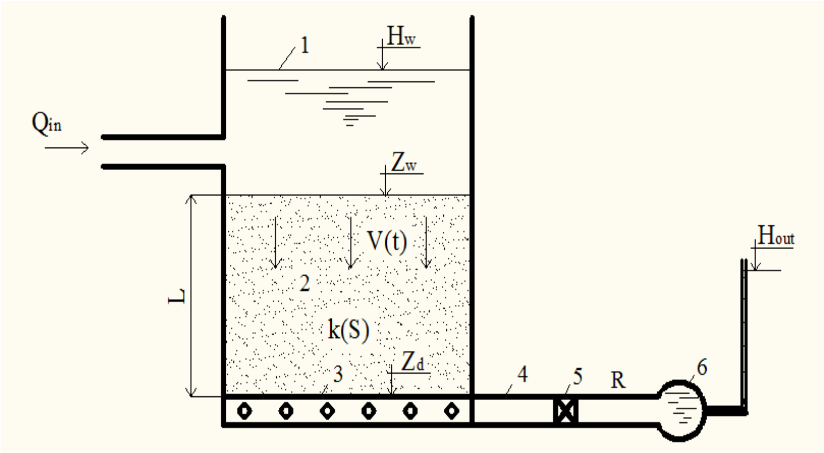


Fig. 1. Scheme of the rapid sand filter: *1* − water level above the filter; *2* – filter medium; *3* − collecting pipeline; *4* − pipelines; *5* − valve; *6* − outflow pipeline

The scheme of rapid sand filter is shown in Fig.1.

The study of rapid filters operations over time has been productively engaged by many scientists [8 − 12]. However, existing calculation methods of these structures are rather approximate and do not include many significant factors.

MATERIALS AND METHODS

In this paper we propose a new approach to the procedure of filtering structures analytical calculation. Mathematical modeling of suspensions clarification in water treatment filters at a filtration velocity that changes significantly over time was conducted [13, 14]. First of all, its variable nature is caused by relatively low filer medium capacity. Thus portion of suspension, which comes into filter under constant discharge, accumulates above medium (Fig.1).

From the very beginning of subsequent filtration cycle water level appears above medium surface, which then during all filtration period gradually increases, what is more irregularly over time. Whereupon the head at the medium inlet accordingly increases, therefore filtration velocity and filter productivity rises. Such filtration intensification is an important result of progressing filter medium siltation and it inevitably leads to the decrease of specified velocity. But specific time slots of water and suspended particles accumulation processes in filter significantly differ, that gives a handle to distinguish the initial stages of water clarification process. Due to its shortness only minimal amount of sediment has time to form in the medium, therefore it is justified to neglect them and considered exceptionally hydraulic aspects of filter operation [15, 16].

For the first stage it is typical for saturated front to form and displace down the medium, which divides it into areas with filled and unfilled by fresh water pores.

The second stage is characterized by fresh water intensive accumulation above the medium surface because of insufficient throughput of as yet factually not silted porous medium.

During the first and the second stage filter is factually only preparing for the third stage of suspension clarification. But because of short duration of the initial two stages they don’t significantly influence the water clarification process on rapid filters. The initial stages are considered in detail in the work [17]. Henceforth the third main stage of filter operation will be considered in the article.

The initial water surface level, which forms above medium, at first rapidly, then slowly increases, forms heightened head at the filter inlet and enhances filtration process. On the contrary, porous bed progressing siltation results in gradual increase of its resistance and, accordingly, in filtration velocity decrease. Thereafter filtration discharge increases during relatively short time period and then monotonically decreases. Significant contribution in general head loss at the filtration structure can form head loss in disposal communications.

Requested mathematical model of suspensions clarification by filtration under variable velocity consists of three interconnected units – clarified, filtration and hydraulic. Such connection is explained by variability and indeterminacy of filtration velocity, whereupon this units can't be solved consequentially (what was usually done when filtration under permanent velocity was analyzed). Thereby analytical methods application is much more complicated.

The clarification unit includes mass transfer equation

$$V(t)\frac{\partial C}{\partial z}+\frac{\partial S}{\partial t}=0, \qquad (1)$$

linear mass exchange kinetics equation

$$\frac{\partial S}{\partial t}=\alpha(V)\cdot C-\beta(V)\cdot S, \qquad (2)$$

and boundary and initial conditions

$$z=0,\ C=C_0; \qquad t=0,\ S=0, \qquad (3)$$

where: *C*, *S* are volume concentrations of suspended and deposited suspension particles; α, β are coefficients of suspended particles adhesion rate and delayed particles separation rate, which according to the literature depend on filtration velocity as follows [18]:

$$\alpha=\alpha_v V^l,\quad \beta=\beta_v V^q, \qquad (4)$$

where: α_v, β_v are appropriate constant coefficients; *l*, *q* are empirical constants, which can take significantly variable values depending on the properties of impurities and mechanisms of their delivery to medium grains.

Suspensions filtration, which takes place in the filter bed with height *L*, is described by the motion equation

$$V(t)=-k(S_S)\frac{\partial h}{\partial z}, \qquad (5)$$

where the variation of filtration coefficient under soiling is determined by the formula

$$k=k_0\left[1-\left(\frac{S_S}{n_0}\right)^{m_1}\right]^{m_2}, \qquad (6)$$

the ratio between the solid particles content in sediment is

$$S_S=\gamma(S)\cdot S, \qquad (7)$$

where: k, k_0 are current and initial filtration coefficients [19]; S_S is volume sediment concentration, which consists of solid particles and bound water; h is piezometric head; n_0 is porosity of uncontaminated medium; m_1, m_2 are empirical coefficients; γ is empirical function which characterizes ratio between sediment content and solid particles in it.

The third unit describes the action of not clarified and clarified water in filtration plant before the inlet of medium and after the outlet of it. At that, it is considered that the head in filtrate collector H_{out} is constant, and the surface layer begins to form immediately $(t=0)$. Then the head at the lower feeding border $(z=L)$, including head loss in outflow communications, looks like

$$z=L,\quad h=H_{out}+R\omega^2V^2, \qquad (8)$$

where R is the resistance of outlet communications; ω is the area of inlet medium surface.

Dynamics of inlet water level is calculated on the basis of its balance equation

$$\omega\frac{dH_w}{dt}=Q_{in}(t)-\omega\cdot V(t), \qquad (9)$$

under the initial condition

$$t=0,\quad H_w=H_m, \qquad (10)$$

where: Q_{in} is water discharge, which comes to the filter; H_w is water level mark over filter bed; H_m is its initial mark (ultimate mark at the second stage).

RESULTS AND DISCUSSION

As the result of approximate problem solution (1) − (10) by analytical methods, the formulas and equations were received in the work [20].

Using modern mathematical analysis software MathCad allows to define all main filtration process characteristics – concentrations, heads, velocities, levels.

The subject of detailed quantitative analysis is main physic-chemical characteristics and technological parameters which are contained in initial model. Only their relative values were calculated: $\bar{\alpha}_v = \alpha_v L \left(\frac{Q_{in}}{\omega}\right)^{l-1}$ – relative adhesion velocity of contamination particles to medium particles; $\bar{\beta}_v = \beta_v \frac{L}{k_0}\left(\frac{Q_{in}}{\omega}\right)^{q}$ – relative suffusion velocity of contamination particles from medium particles; $\bar{t} = \frac{Q_{in}t}{\omega n_0 L}$ – relative time slot; L – filter bed height; $\bar{C} = \frac{C}{C_0}$ – relative contamination concentration; C_0 – initial contamination concentration; $\psi_v = \frac{n_0 L}{\Delta h_0}$; $\Delta h_0 = Z_w - H_{out}$ – head scale; Z_w – inlet surface medium mark; H_{out} – head in filtrate collector; $\bar{R} = \frac{k_0^2\omega^2\Delta h_0 R}{L^2}$ – disposal communications relative resistance.

Definitional domains of desired characteristics were selected wide enough. It allows to indicate physic-chemical factors which either improve or complicate clarification process. But due to the limited volume of the article, only the most important relations are illustrated, which directly follow from the filtration task solution under variable velocity over time.

At that the following model parameters were fixed: $\bar{\beta}_v = 0{,}01$, $q = 1$, $\bar{\gamma} = 0{,}001$, $\bar{R} = 1$, $\psi_v = 0{,}5$. For exponent *l* from equation (4) the average of the known in literature value was accepted.

Variation of suspended particles concentration in filtrate, filter productivity, amount of not clarified suspension which accumulates above medium is shown in the first calculation series. The filtration medium sorption capacity varieties from medium $(\bar{\alpha}_v = 5)$ to high $(\bar{\alpha}_v = 9)$.

Fig.2 illustrates the dependence of relative final concentration $\bar{C}_e$ from relative time slot $\bar{t}$.

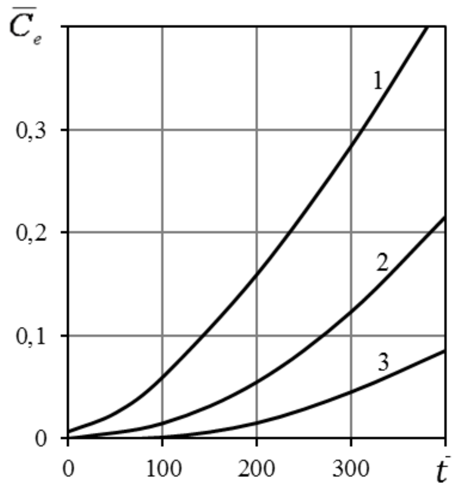


Fig.2. Relative final concentration in relation to relative time slot: *1* – $\bar{\alpha}_v = 5$; *2* – $\bar{\alpha}_v = 7$; *3* – $\bar{\alpha}_v = 9$

It allows to draw conclusions, firstly, of the significance of suspended particles primary skip through medium layers, secondly, of deterioration of its separation quality. Obviously the greatest skip takes place under the least value $\bar{\alpha}_v = 5$ (curve 1). In this case less amount of sediment is formed in the filter bed and it allocates much more evenly by its height.

Fig.3 illustrates the dependence of relative filtration velocity from time slot.

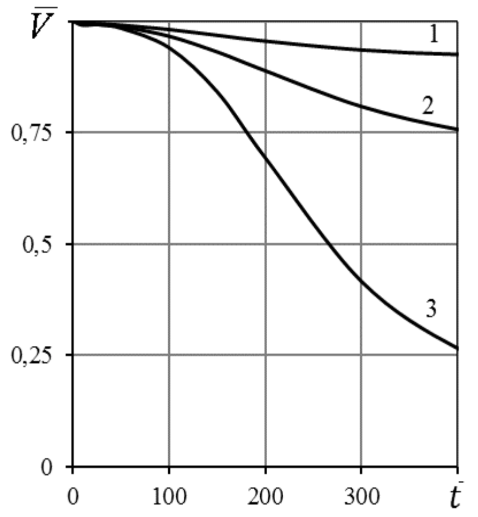


Fig.3. Relative filtration velocity in relation to relative time slot: *1* – $\overline{\alpha}_V = 5$; *2* – $\overline{\alpha}_V = 7$; *3* – $\overline{\alpha}_V = 9$

Under not big sorption capacity values (curve 1) minimal filtration velocity decrease over time takes place. Intensified impurities sedimentation on the top part of filter medium (under great $\overline{\alpha}_V$ values, curve 3) leads to sharp filtration velocity and filter productivity decrease.

Fig.4 illustrates the dependence of relative water level above filter medium from relative time slot.

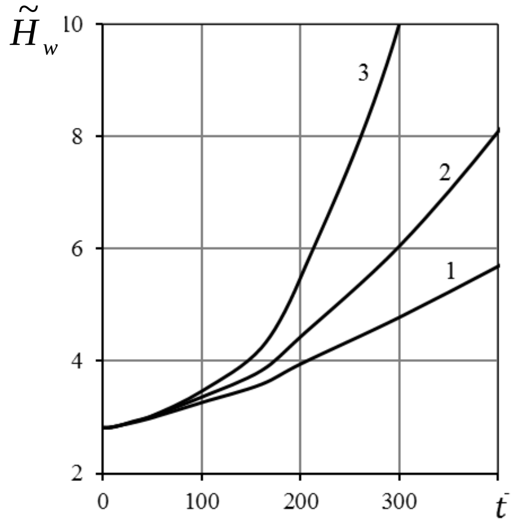


Fig.4. Relative water level above filter medium in relation to relative time slot: *1* – $\overline{\alpha}_V = 5$; *2* – $\overline{\alpha}_V = 7$; *3* – $\overline{\alpha}_V = 9$

It witnesses about the considerable increase of water level rise velocity above the medium under increasing material adhesive properties.

On the basis of the derived solution, engineering method for the proof of technological time slots, namely, the time slot of medium protecting action $\bar{t}_p$, the time slot of achieving head loss in filter bed its limit value $\bar{t}_v$ and, most important, the filtration cycles duration $\bar{t}_f$, was elaborated. Moreover, the filtration cycle duration should be assumed the smaller of these two technological time slots. Quality and efficiency criteria of filters operation were involved for this. They regulate the increasing content of suspended solids in the filtrate and filter productivity degradation. That is, by technical and economic calculations it is possible to define specific filtering velocity $\overline{V}_*$, that with less velocity filter further work will be uneconomical.

In the theoretical analysis of clarifying filter effect aforementioned economic criteria should be complemented by quality criteria, which is governed by suspension content in the filtrate. Its observance means, that the concentration of suspension at the medium outlet will not exceed the normative value. For normal filters operation it is necessary to fulfill both criteria simultaneously. Therefore, the key importance is to study patterns of hydrodynamic and physicochemical processes which proceed in the filter bed and over it.

The subject of particular quantitative analysis was physical and chemical characteristics, which were contained in the original model, as well as technological time slots and filtration cycle duration.

Fig.5 shows the dependence of the relative protective action time slot of filter bed $\bar{t}_p$ from its adhesive properties $\overline{\alpha}_V$ under various relative suspension separation velocity $\overline{\beta}_V$. These graphs attest that increasing of relative velocity of inhibited pollutants separation increases the suspension concentration in filtrate, and, consequently, reduces the relative time slot of medium protective action.

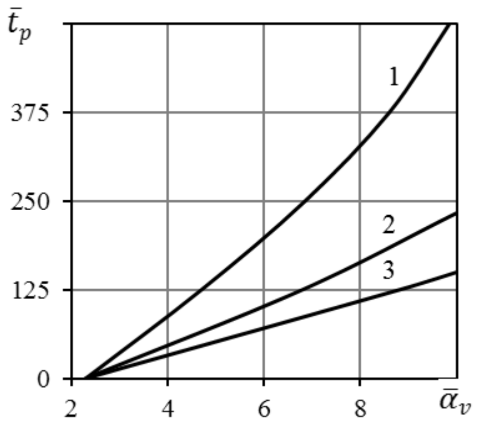


Fig.5. $\bar{t}_p$ relation to $\overline{\alpha}_v$ under various relative velocities of suspension separation: *1* – $\overline{\beta}_v = 0{,}01$; *2* – $\overline{\beta}_v = 0{,}02$; *3* – $\overline{\beta}_v = 0{,}03$

Fig.6 illustrates the dependence of the relative time slot of filtration velocity decrease $\bar{t}_v$ from adhesive properties of filtering material $\overline{\alpha}_v$ under various relative filtration velocities $\overline{V}_*$. These curves $\bar{t}_v(\overline{\alpha}_v)$ show a sharp time slot decrease $\bar{t}_v$ under increasing adhesive properties of filter bed. Under high values of $\overline{\alpha}_v$ time slot of effective filter work can significantly decrease.

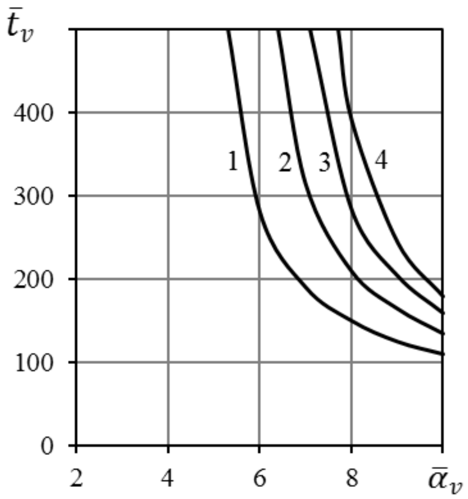


Fig.6. $\bar{t}_v$ relation to $\overline{\alpha}_v$ under various relative filtration velocities: *1* – $\overline{V}_* = 0{,}9$; *2* – $\overline{V}_* = 0{,}8$; *3* – $\overline{V}_* = 0{,}7$; *4* – $\overline{V}_* = 0{,}6$

Comparison of the curves in Figures 5 and 6 allows approximately determine the intersection points and appropriate optimal values of filtration cycle duration $\bar{t}_f$ and relative coefficient of particles adhesion velocity $\overline{\alpha}_v$.

In practice, the reliable value of $\bar{t}_f$ allows to start regular filter washing in proper time and thereby to use its clarified resource as much as possible.

However, methods, which follow from this equations and are calculated for theoretical justification of technological time slots and filter bed measure, especially its technologically rational height L, have the greatest practical importance. These methods are illustrated by technological time slots calculations as functions of the filter material adhesive properties and innovation construction parameter of relative filter bed height $\overline{L}$, which is equal to ratio of arbitrary value L to its minimum calculated value $L_{\min}$.

Further two typical situations will be considered. They are caused by real opportunities of filtration material supply. In the first case it was received from local manufacturing wastes. So it is cheap and available in almost unlimited amounts. In the second more typical case filtration material is scarce and expensive. So it is necessary to achieve maximum efficiency of filtration material (fix its operating volume) by economical use.

In the first case medium height and volume vary synchronously under constant other parameters.

Theoretical justification methodology of filter bed height is illustrated by the example of calculation of relation to relative filtration cycle duration $\bar{t}_f$ and relative feeding height $\overline{L}$ under various filter material adhesive properties (Fig.7).

At low protective filter feeding capacity ($\overline{\alpha}_v = 5$, curve 1) the duration of filter operation is limited by filtrate quality ($\bar{t}_f = \bar{t}_p$). At high protective filter material capacity ($\overline{\alpha}_v = 9$, curve 3) the opposite pattern is observed and filtration cycle duration is limited only by filter efficiency decrease ($\bar{t}_f = \bar{t}_v$). At intermediate value $\overline{\alpha}_v = 7$ (curve 2), in the beginning filtering process is limited by medium protective properties, later on – by its soiling, and as a result, filtration velocity decreasing. Thus, at the first interval $\bar{t}_f = \bar{t}_p$, at the second interval – $\bar{t}_f = \bar{t}_v$.

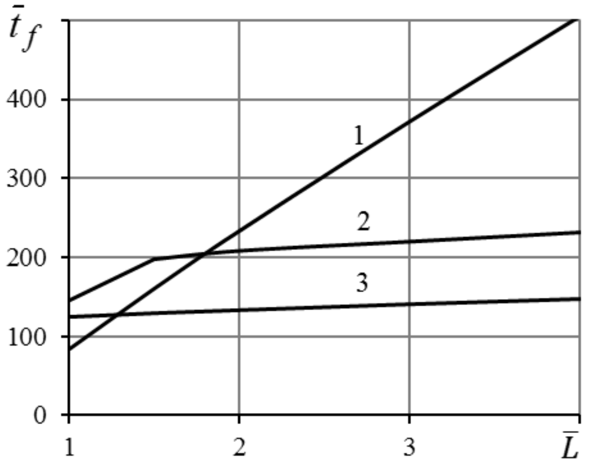


Fig.7. Relation $\bar{t}_f\left(\bar{L}\right)$: *1* – $\bar{\alpha}_v = 5$; *2* – $\bar{\alpha}_v = 7$; *3* – $\bar{\alpha}_v = 9$

It is obvious, that at low filter material adhesion capacity, the increase of $\bar{L}$ leads to sharp filtrate quality improvement and, as the result, extension of filter uninterrupted operation (curve 1). In the case of mild or high adhesive material capacity, the increase of $\bar{L}$ affects filtration cycle duration $\bar{t}_f$ much less (curves 2, 3), at that, obviously curve 2 prevails, due to more even sediment distribution in the feeding.

Fig.8 illustrates the case with fixed volume.

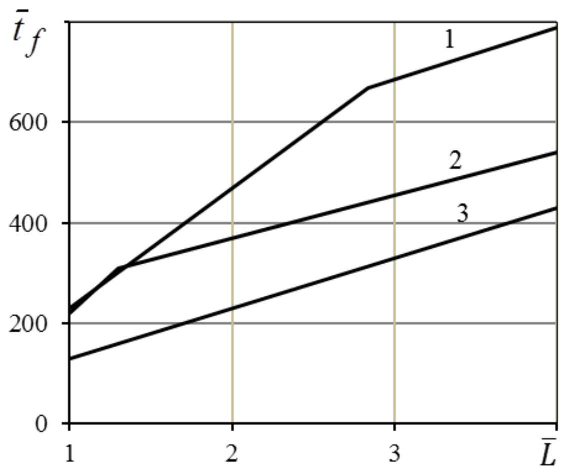


Fig.8. Relation $\bar{t}_f\left(\bar{L}\right)$: *1* – $\bar{\alpha}_v = 5$; *2* – $\bar{\alpha}_v = 7$; *3* – $\bar{\alpha}_v = 9$

In the second case in technological calculations it is necessary to consider that operating volume is constant (*W*=const). Only medium height and concerted medium surface area are varied.

At high protective capacity (curve 3) the filtration cycle duration of filtration cycle is analogously limited only by filter efficiency decrease ($\bar{t}_f = \bar{t}_v$). At low and intermediate protective feeding capacity (curve 1, 2), at first the filtering process is limited by medium protective properties, later on – by its soiling, and as a result, filtration velocity decreasing. Thus, at the first interval $\bar{t}_f = \bar{t}_p$, at the second interval – $\bar{t}_f = \bar{t}_v$.

The increase of medium height leads to medium surface area decrease and filtration velocity increase. At the same time suspended particles adhesion and sediment particles suffusion increases. It explains higher location of analogous curves at Fig.8.

CONCLUSIONS

1. Filter productivity can essentially vary over time without velocity regulators. Disposition of such variations complicates because of not clarified water accumulation above the medium layer. Intensive raise of water level and appropriate filtration velocity increase takes place mainly at the beginning of filtration cycle. Then because of progressing filtration material sedimentation this velocity decreases gradually and greatly.

2. There are two initial stages of suspension clarification before the main one. Formation of surface water layer under medium pores filling takes place during the first stage. The rapid raise of this layer under almost clean medium takes place during the second stage.

3. Derived analytical solution of a mathematical filtering task allows to predict the spatial and temporal variations of main filtration characteristics: suspended and sediment particles concentrations, filtration discharge dynamics and water level above medium.

4. The key technological parameter is filtration cycle duration, which should be deter-

mined on the basis of clarified water quality criteria and filter operating efficiency.

5. Based on the derived relations, calculation methods of filter medium protective action time slot, achieving the maximum admissible head loss, filtration cycle duration and rational filter bed height were evolved.

6. Summarizing the results of numerous calculations, it can be maintained that unsuccessful choice of filtering material can lead to a significant reduction of filter continuous operation time slot and, as the result, wash water over-expenditure.

7. It is seen from analysis of relations $\bar{t}_p$, $\bar{t}_v$, $\bar{t}_f$ from the value $\bar{L}$, that $\bar{L}$ increasing is able to improve the filtrate quality to a great extend, increase head loss to a lesser degree. But final selection of value $\bar{L}$ in this case is possible only including feeding value and its washing energy loss. If filter medium volume and filter productivity are considered to be constant, the necessity of technical and economical approach to justification of rational value $\bar{L}$ disappears.

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Работа фильтровальных сооружений в режиме изменения скорости со временем

Александр Кравчук

Аннотация. Одними из основных сооружений, которые используются для подготовки воды необходимого качества, являются скорые фильтры. Работа таких сооружений, как правило, происходит в безнапорном режиме. Время работы фильтра зависит от двух основных параметров: качество очистки воды и обеспечение необходимого расчетного расхода. При этом принимается, что скорость движение жидкости в теле фильтра является постоянной. В реальности характер работы таких сооружений может отличаться от рассмотренных. В представленной работе проанализирован вариант работы скорого фильтра при существенно изменяющейся со временем скорости фильтрования. Рассмотрены конкретные условия работы таких сооружений и дифференциальные уравнения, которые описывают процесс движения воды в фильтрующей среде и интенсивность удаления загрязнений из нее.

В результате проведенного анализа показано изменение со временем концентрации взвешенных веществ в фильтрате, производительности фильтра, количества неосветленной суспензии, которое накопилось над загрузкой при разных значениях сорбционной способности фильтрующего материала. Предложена методика инженерного расчета основных характеристик фильтрующих сооружений, в том числе технологических времен фильтрования, длительности фильтроцикла и оптимальной высоты фильтрующей загрузки. Приведенные расчетные зависимости и уравнения иллюстрируются серией примеров с типичными исходными данными.

Ключевые слова: фильтрация, суспензия, осадок, фильтроцикл, фильтрат.