За допомогою теоретичних досліджень обґрунтовано ефективність застосування в швидких фільтрах із зернистим завантаженням вертикальних дренажних елементів з пористими волокнистими оболонками. Представлено математичну модель паралельного фільтрування малоконцентрованої суспензії через зернисте та волокнисте середовища. На основі числових експериментів визначено значущі параметри фільтру вдосконаленої конструкції. Показані приклади розрахунків раціональних значень основних параметрів

Ключові слова: швидкий фільтр, вертикальний дренажний елемент, пориста волокниста оболонка

С помощью теоретических исследований обоснована эффективность применения в скорых фильтрах с зернистой загрузкой вертикальных дренажных элементов с пористыми волокнистыми оболочками. Представлена математическая модель параллельного фильтрования малоконцентрированной суспензии через зернистую и волокнистую среды. На основе численных экспериментов определены значимые параметры фильтра усовершенствованной конструкции. Показаны примеры расчетов рациональных значений основных параметров

Ключевые слова: скорый фильтр, вертикальный дренажный элемент, пористая волокнистая оболочка

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RESEARCH INTO THE INFLUENCE OF VERTICAL DRAINAGE ELEMENTS ON THE OPERATIONAL EFFICIENCY OF RAPID FILTERS

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1. Introduction

In the preparation of drinking water from surface sources, an important stage of treatment is filtering through a granular filter layer. Such a technique of purification, in combination with coagulation, enables effective removal of finely dispersed suspended particles. At elevated turbidity of raw water, filtration is used for post-purification after preliminary clarification of water by deposition or in a layer of suspended sediment [1, 2].

The water treatment plants commonly use rapid filters in which filtering is performed at a rate of 2–15 m/h [3, 4]. These plants widely apply silica sand as a filter layer. As the purified water passes through a filtering layer, suspended solids “stick” to the grains of a filter layer, which reduces porosity but increases head losses in the structure. If the filter layer’s thickness is insufficient while the filter layer grains are large in size, there occurs a “breakthrough” of contaminants into the filtrate. Head losses that exceed the critical value or a change in the quality of the filtrate that is below the set magnitude are the condition for the transfer of the filter from a filtering regime to a regeneration mode. Using a water or air-water washing, captured contaminates are washed out of the granular layer, thereby restoring its filtering and retrieving abilities. The washing is carried out within a short period, but its intensity is approximately 10 times larger than the intensity when filtering [1, 3]. The result is a significant amount of washing water (up to 10 % of the volume of treated water). Additional facilities and equipment are required to treat and pump the water used for the regeneration of rapid filters. These expenditures are additionally increased by the lost profit due to the fact that the treated water, rather than selling it to the consumer, is utilized for own needs of the water treatment plant. The specified factors render rapid filters among the most expensive facilities in water treatment technologies. Recently, especially in Ukraine, the cost of services to provide drinking water has been continuously increasing. This is due to inflation, increased prices for electricity, the need to employ expensive imported reagents, and other factors. Reducing the amount of washing water in rapid filters will to a certain degree make it possible to bring down the rising cost of water to consumers. Therefore, it is an important task to explore ways to solve a given problem.

2. Literature review and problem statement

Among various solutions to reduce the amount of washing water in the regeneration of rapid filters, one can distinguish two directions. The first is a decrease in the number of washings by increasing the duration of operation of a plant under filtration mode. The second one implies direct improvement of the washing process.

Let us consider the first direction. We should select the methods aimed at increasing contaminant capacity of a granular filter layer by more uniform distribution of captured contaminants along its thickness. This can be achieved by applying some solutions that make it possible for the head losses and quality of the filtrate to reach critical values in a synchronized fashion. Such solutions include the following.

1) Filtration in an ascending flow [5]. In this case, at the beginning of a filtering cycle there is a high probability that the filter layer expands and contaminants "break through" into the filtrate.

2) Multiflow filtering [6], including diverting part of the flow to the lower layers [7]. Drainage-distributing system is located in the thickness of a filter layer, and part of the working height is not used for purification. Other disadvantages of this method are the colmatation of a drainage system or the possibility for the filter layer grains to penetrate the filtrate.

3) Multistage filtering [8]. Each type of a filter layer requires a separate facility, the result being an increase in their number and a complicated structural scheme.

4) Application of designs where the filtering and flushing are implemented in perpendicular directions [9]. Porous partitions that separate the layers during washing prevent their mixing layers. It is possible to flush each layer separately as it is polluted. However, this requires a more elaborate design to prevent washing water overflow between the layers.

5) Application of a double-layer (or layered) filter layer with a decreasing grain size in the direction of filtration. The main disadvantage of a given technique is mixing layers when flushing. To reduce the possibility of mixing, materials with different densities are employed, such as anthracite (layer 1) and quartz sand (layer 2) [10, 11]. The first layer may contain the less costly, in comparison with anthracite, local materials: coconut shell [12], burnt palm bark [13], charcoal [14], etc. In addition to the difference in densities, grain filter layer must possess the required porosity, homogeneity, and resistance against abrasion. Meeting all the requirements limits the choice of existing filtering materials of natural origin. For a multilayer filter layer, cheaper materials of artificial origin, as well as those with various characteristics, are used: broken glass [15], granules of polystyrene [16] or polyvinyl chloride [17]. However, the difference in densities of the first and the second layer leads to yet another problem rather than mixing. The degree of expansion of the less dense upper layer is larger when flushing. As a result, it is required to place the grooves that remove the washing water at a higher level, this increases the possibility that the filter layer grains are washed away.

Porous fibrous polymeric materials can be employed to act as a filter layer, as an alternative to the grainy media [18]. Purification quality is not inferior to the effectiveness of filtering through quartz sand or granules of foam polystyrene. Fibrous materials have far greater porosity; it is possible to fabricate porous partitions in a wide range of pore sizes, including a variable magnitude; it excludes washing away the particles of a filter layer and the mixing of layers when flushing. However, in order to regenerate a filtering layer made of fibrous material with a large thickness, it is required to conduct a more intensive washing, compared with a granular filter layer.

To prevent uneven washing and the formation of sludge accumulation zones, the drainage-distributing systems with shells made of fibrous porous polymeric materials have been actively used over the past two decades. It seems appropriate to use these shells not only to distribute the washing water evenly and to cut off the filter layer grains, but also for the post-purification of water that passed through the granular layer [19]. Suspended particles have a size much smaller than the filter layer grains. To cut them off, pores of the fibrous shells must be reduced. This leads to an increase in head losses that can be compensated for by increasing the filter layer grain size and by applying a multilayer shell whose layer that captures the suspension has a small thickness.

On the other hand, it is possible to avoid problems that occur when the purified water passes sequentially through a granular layer and a fibrous layer by organizing parallel filtering. To do this, it is required to arrange in the thickness of a granular filter layer vertical drainage elements with fibrous porous shells. The effectiveness of this solution requires scientific justification. There are various mathematical models that describe the process of filtering through granular [20, 21] and fibrous media [22, 23]. However, these models are hardly applicable to describe the parallel filtering of a low-concentrated suspension.

3. The aim and objectives of the study

The aim of the research undertaken is the justification of the effectiveness of parallel filtering through a granular filter layer and porous shells made of fibrous materials when purifying water from suspended solids.

To achieve the set aim, the following tasks have been solved:

– to develop a circuit of the rapid filter with vertical drainage elements (VDE);

– to construct a mathematical model that would describe the process of water purification by filtering during which the flows pass in parallel through a grainy filter layer and porous fibrous shells (PFS);

– based on the mathematical model, to conduct numerical experiments; based on their analysis, to substantiate rational parameters of the device at which its effectiveness is maximal.

4. Materials and methods to study parallel filtering of a low-concentrated suspensions through granular and fibrous media

We shall consider a rapid filter that contains a filter layer, made of granular material, with vertical cylindrical drainage elements with porous shells made of polymeric fibrous materials (Fig. 1).

The layer of water in the over-the-filter space creates a head under which the purified suspension is filtered in parallel through a granular filter layer (1) and PFS VDE (2). The flow rate that passes through VDE increases in the direction of filtering. Consequently, the speed of filtering in the granular layer decreases by its height. During this process, the filtering media are colmatating. As PFS is polluted, the load on the granular layer increases with the pollution front moving downwards. Water from VDE is collected and removed by a system of pipelines (3), and the filtrate that has passed the layer of the granular filter is discharged through a drainage system (4). The same system is used for the separation of water fed during regeneration of the granular layer. The washing water that contains contaminants washed from the granular layer, is discharged through a system of grooves (5). Flushing the granular filter layer is conducted in line with a standard procedure. PFS are cleaned due to the friction of the filter layer particles, agitated in flushing, and a short water pulse in reverse direction at the end of the granular layer regeneration.

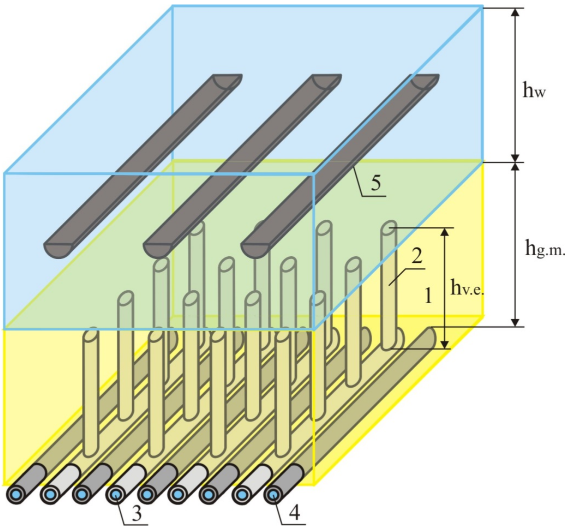

Fig. 1. Schematic of the rapid filter with VDE: 1 — layer of granular filter layer; 2 — VDE; 3 — system for removing the water filtered through VDE; 4 — system for removing the water filtered through a granular filter layer; 5 — grooves to discharge washing water; $h_{g.m.}$ — working height of the granular filter layer; $h_{v.e.}$ — VDE working height; h_w — height of the layer of water above a granular filter layer

When constructing a mathematical model of work of the filtration structure, shown in Fig. 1, we accept the following simplification and assumptions:

1. Filtering in a granular filter layer is performed from top to bottom, part of the flow is discharged by VDE. VDE are evenly arranged in a granular layer; their influence on the structure of the filtration flow in horizontal direction can be neglected. Concentration of suspended solids in the purified water and filter layer grains depends only on the height and does not change over area of the filter. Such an approach makes it possible to model the process by using one-dimensional equations recorded in in a rectangular coordinate system.

2. Filtering through PFS proceeds with the formation of a layer of sludge on their surface. The thickness of a layer of sludge is the same in the horizontal direction and depends only on the vertical coordinate.

3. The flow of purified fluid through a granular filter layer and PFS occurs under a laminar mode.

4. Contribution of diffusion in the transport of suspended solids during filtration in a granular filter layer of the system is small compared to other components.

5. In a granular filter layer, the mass transfer kinetics of suspended solids from the liquid phase to the solid phase is described by a linear dependence.

6. When passing through a granular filter layer, all particles in the suspension are captured equiprobably regardless of size, which is why it is possible to accept the distribution of particles of the suspension in the water fed to PFS to be the same as in the original. The structure of sediment at the surface of PFS over the entire height of VDE is the same, only its thickness changes.

7. Resistance of the drainage system (4) (Fig. 1) can be neglected.

8. Performance efficiency of the structure is constant over the entire time of filtration mode.

9. PFS has a layered structure and consists of an outer thin layer with the rating of filtering that ensures the required degree of purification, and an interior substrate with a large pore size. The substrate's resistance can be neglected.

10. At the beginning of a filtering cycle residual concentration of suspended substances in the filter layer grains and at the surface of PFS is zero.

With respect to the assumptions accepted, a mathematical model of the process of parallel filtering of a low-concentrated suspension through a granular filter layer and PFS VDE is based on the following equations and dependences.

1) Relationship between flow rate of the filtered water (or the speed of filtration) and head losses is described by the filtration equation. For any point with coordinate z, which varies from 0 to $h_{g.m.}$, one can write filtration equation in the form:

– for the granular layer

$$Q_{g.m.}(z,t)=\frac{F_{g.m.}\rho g\Delta h(z,t)}{\mu R_{g.m.}(z,t)}; \quad (1)$$

– for PFS

$$dQ_{v.e.}(z,t)=\frac{dF_{PFS}\rho g\Delta h(z,t)}{\mu\left(R_{PFS}+R_s(z,t)\right)}, \quad (2)$$

where $Q_{g.m.}(z, t)$ is the flow rate of water, which passes through a granular filter layer of thickness dz, m^3/s; $dQ_{v.e.}(z, t)$ is the elementary water flow rate, which passes through elementary area $dF_{PFS}=\pi N_{v.e.}d_{PFS}dz$ (m^2), of PFS, m^3/s; d_{PFS} is the diameter of VDE, m; $N_{v.e.}$ is the number of VDE;

$$F_{g.m.}=F-\frac{\pi N_{v.e.}d_{PFS}^2}{4}$$

is the surface area of a granular filter layer, m^2; F is the cross-sectional area of the working chamber of the filter, m^2; $\Delta h(z, t)$ are the head losses at a section from z to $h_{g.m.}$, m.; μ is the dynamic viscosity, Pa·s; ρ is the density of the filtered suspension, kg/m^3; g is the acceleration of free fall, m^2/s; $R_{g.m.}(z, t)$ is the resistance of a granular filter layer, m^{-1}; R_{PFS} is the resistance of PFS, m^{-1}; $R_s(z, t)$ is the resistance of the layer of sediment at the surface of PFS, m^{-1}; t is the time, s; z is the vertical coordinate, m.

At each point with coordinate z, the flow rate of water passing through a granular filter layer is equal to

$$Q_{g.m.}(z,t)=Q-Q_{v.e.}(z,t), \quad (3)$$

where Q is the filter performance, m^3/s; $Q_{v.e.}(z, t)$ is the flow rate of water passing through VDE at a section from 0 to z, m^3/s.

During parallel filtering of suspension through PFS and a granular layer, the condition for equality of pressure losses on both directions is satisfied. Thus, with respect to dependences (1)–(3), we can record

$$\left(Q-Q_{v.e.}(z,t)\right)\frac{R_{g.m.}(z,t)}{F_{g.m.}}=dQ_{v.e.}(z,t)\frac{R_{PFS}+R_s(z,t)}{\pi N_{v.e.}d_{PFS}dz}. \quad (4)$$

By integrating equation (4), we obtain a dependence to determine water flow rate that passes through VDE

$$Q_{v.e.}(z,t)=Q\left(1-e^{-\frac{\pi N_{v.e.}d_{PFS}}{F_{g.m.}}\int_0^z \frac{R_{g.m.}(z,t)}{R_{PFS}+R_s(z,t)}dz}\right). \tag{5}$$

Substituting (3) and (5) in expression (1), we obtain the equation of filtration for parallel filtering

$$Q=\Delta h(z,t)\frac{\rho g}{\mu}\frac{F_{g.m.}}{R_{g.m.}(z,t)}e^{\frac{\pi N_{v.e.}d_{PFS}}{F_{g.m.}}\int_0^z \frac{R_{g.m.}(z,t)}{R_{PFS}+R_s(z,t)}dz}. \tag{6}$$

2) Resistance of the granular layer, PFS, and the layer of sediment at the surface of PFS, is determined from dependences

$$R_{g.m.}(z,t)=\int_z^{h_{g.m.}} r_{g.m.}(z,t)\mathrm{d}z;$$

$$R_s(z,t)=r_s h_s(z,t);\quad R_{PFS}=r_{PFS}h_{PFS}, \tag{7}$$

where $r_{g.m.}(z, t)$ is the specific resistance of the colmatated a granular filter layer, m^{-2}; r_s is the specific resistance of sediment at the surface of PFS, m^{-2}; r_{PFS} is the specific resistance of PFS, m^{-2}; $h_s(z, t)$ is the thickness of a layer of sediment, m; h_{PFS} is the thickness of PFS, m.

3) Specific resistance of the non-colmatated filter layer and the layer of sediment is defined from the dependence of Kozeny-Karman

$$r_{0g.m.(s)}=k_1F^2_{un.g.m.(s)}\frac{(1-n_{0g.m.(s)})^2}{n^3_{0g.m.(s)}}, \tag{8}$$

where $n_{0g.m.(s)}$ is the porosity of the non-colmatated granular filter layer (or sediment at the surface of PFS);

$$F_{un.g.m.(s)}=\frac{6\Phi}{d_{g.m.(s)}}$$

is the specific surface of the filter layer grains (or sediment particles at the surface of PFS), m^{-1}; Φ is the shape factor, for spherical particles Φ=1; k_1 is the ratio of pore length to its diameter; $d_{g.m.(s)}$ is the equivalent diameter of the filter layer grains (or sediment particles at the surface of PFS), m.

To determine specific resistance of PFS, in which the estimated parameter is not the size of a filter layer particle but the equivalent diameter of pores, we obtained formula [24]

$$r_{PFS}=\frac{k_1F^2_{un.PFS}}{n_{PFS}}, \tag{9}$$

where n_{PFS} is the porosity of PFS; $F_{un.PFS}$ is the specific pore surface of PFS, m^{-1}.

4) It is possible to calculate specific resistance of the colmatated granular filter layer from dependence [25]

$$r_{g.m.}(z,t)=r_{0g.m.}\left(\frac{n_{0g.m.}}{n_{g.m.}(z,t)}\right)^3, \tag{10}$$

where $n_{g.m.}(z, t)$ is the porosity of the colmatated granular filter layer.

5) A change in the porosity of a granular layer as a result of colmatation by the captured suspension is determined from expression

$$n_{g.m.}(z,t)=n_{0g.m.}-\frac{S(z,t)}{\gamma}, \tag{11}$$

where γ is the concentration of suspended particulate matter in the sediment, kg/m^3; $S(z, t)$ is the concentration of suspended particles captured on the grains of a filter layer, kg/m^3.

6) A change in the concentration of suspended particles on the grains of the filter layer is determined from the equation of mass transfer of suspended particles from the liquid phase to the solid phase

$$\frac{\partial S(z,t)}{\partial t}=b(z,t)C(z,t)-a(z,t)S(z,t), \tag{12}$$

the equation of suspended particles transfer by a flow of the filtered fluid makes it possible to calculate the concentration of suspended solids in the purified water

$$n_{g.m.}(z,t)\frac{\partial C(z,t)}{\partial t}+V(z,t)\frac{\partial C(z,t)}{\partial z}+\frac{\partial S(z,t)}{\partial t}=0, \tag{13}$$

where $C(z, t)$ is the concentration of particles suspended in the filtered fluid, kg/m^3;

$$V(z,t)=\frac{Q_{g.m.}(z,t)}{F_{g.m.}}$$

is the filtration speed, m/s; $a(z, t)$ and $b(z, t)$ are the coefficients, respectively, of detachment and adhesion of particles in the suspension to the grains of a filter layer, s^{-1}

7) Coefficients $a(z, t)$ and $b(z, t)$ are defined from dependences:

$$a(z,t)=\frac{V(z,t)}{d_{g.m.}}\alpha;\quad b(z,t)=\frac{\beta}{\left(V(z,t)\right)^{0,7}d^{1,7}_{g.m.}}V(z,t), \tag{14}$$

where α and β are coefficients that account for the physical-chemical properties of filter layer grains and the suspension filtered through it.

8) Thickness of the sediment layer formed by the deposition of suspended matter at the surface of PFS is equal to

$$h_s(z,t)=\frac{C(z,t)-C_{cr}}{\pi N_{v.e.}d_{PFS}\rho_s n_{0g.m.}}\int_0^t\frac{dQ_{v.e.}(z,t)}{dz}\mathrm{d}t, \tag{15}$$

where C_{cr} is the concentration of suspended solids in the filtrate, kg/m^3; ρ_s is the density of the sediment captured at the surface of PFS, kg/m^3.

To solve equations (6), (12, (13), the following boundary conditions are accepted.

Initial conditions: at t=0 $C(z, 0)=C_{cr}$; $S(z, 0)=0$.

Distribution of head losses for the thickness of a granular filter layer at the beginning of a filtering cycle is described by expression

$$\Delta h(z,0)=Q\frac{\mu}{\rho g}\frac{r_{0g.m.}\left(h_{g.m.}-z\right)}{F_{g.m.}}e^{-\frac{\pi N_{v.e.}d_{PFS}r_{0g.m.}}{F_{g.m.}R_{PFS}}\left(h_{g.m.}z-\frac{z^2}{2}\right)}.$$

Boundary conditions: at z=0 $C(0, t)=C_0$ (source water turbidity), $S(0, t)$ is determined from equation (12).

Thus, the system of equations and dependences (2), (3), (5)–(15), as well as the boundary conditions, underlie a mathematical model of the water purification process by parallel filtering through a granular filter layer and PFS.

To implement the mathematical model numerically, we introduced a grid (a discrete set of nodal points) in the region of change in the independent variables. Differential equations were replaced with approximate finite-difference analogues. Instead of functions of continuous argument, values for the desired parameters were found in the nodes of the grid.

In addition, at each time step, we employed the iteration method until the relative error exceeded the given value. At the first step of the iteration values of unknown parameters were taken equal to the values at the previous time step.

5. Results of theoretical study into effectiveness of operation of the rapid filter with VDE

Using the mathematical model constructed, we studied the effectiveness of application of the filtering structure with VDE.

The criterion of effectiveness was selected to be the magnitude representing the ratio of duration of operation between washings of the filter with VDE T_2 to the same parameter for the filter of traditional design T_1 (no VDE).

Parameters for a granular filter layer in the filter of traditional design were chosen in such a way that the duration of its filtering mode has a maximum value. A decline in the quality of the filtrate below an acceptable level ("break-through" of contaminants) occurs approximately at the same time with the achievement of head losses limits. This allows a more objective comparison.

We also took into account that VDE, similarly to a granular filter layer, require washing. As previously stated, flushing VDE is carried out by the reverse current of water (from the inside to the outside) and has a less duration in comparison with a granular filter layer washing. Introduce parameter $\eta=T_{v.e.}/T_{g.m.}$, which represents the ratio of VDE washing duration to the washing duration of a granular filter layer. Therefore, parameter T_2/T_1 should be adjusted

$$\frac{T_2}{T_1}=\left(\frac{T_2}{T_1}\right)'\frac{1}{1+\eta\frac{F_{VDE}}{F_{g.m.}}\frac{\omega_{VDE}}{\omega_{g.m.}}},$$

where $\left(\frac{T_2}{T_1}\right)'$ is the efficiency criterion without considering additional water consumption for washing PFS; $F_{PFS}=\pi N_{v.e.}d_{PFS}h_{v.e.}$ is the surface area of PFS, m^2; ω_{VDE} is the intensity of washing PFS VDE, (m^3/s)/m^2; $\omega_{g.m.}$ is the intensity of washing a granular filter layer, (m^3/s)/m^2.

It was accepted in the calculation that the intensity of washing PFS and the intensity of washing a granular filter layer are equal. The following structural and technological parameters were considered to be the basic factors: equivalent diameter of grains in a granular filter layer, surface area, parameter η, working height of the drainage element. Values of these parameters changed in the following ranges: $d_{g.m.2}=(1.0\div1.25)d_{g.m.1}$; $F_{PFS}=(1.25\div5.0)F_{g.m.}$; $\eta=0.05\div0.15$; $h_{v.e.}=(0.5\div1.0)h_{g.m.}$.

Magnitudes of other parameters were taken to be constant:

– equivalent diameter of grains in a granular filter layer at which duration of the operation of filter with traditional design without washing is maximum $d_{g.m.1}=0.79\times10^{-3}$ m;

– working height of a granular filter layer $h_{g.m.}=1.3$ m;

– cross-sectional area of the filter working chamber $F=40$ m^2;

– filter performance $Q=0.08$ m^3/s;

– porosity of a granular filter layer $n_{0g.m.}=0.4$;

– PFS porosity $n_{PFS}=0.7$;

– equivalent diameter of PFS pores $d_{PFS}=5\times10^{-6}$ m;

– equivalent diameter of sediment particles $d_s=5\times10^{-6}$ m.

Fig. 2 shows an example of calculation of dependence of the efficiency of application of VDE on the grain size in a granular filter layer and the resultant surface area $F_{PFS}/F_{g.m.}$.

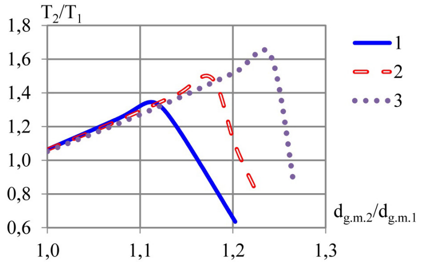

Fig. 2. Influence of grain size and surface area of PFS on effectiveness of the operation of filter with VDE: 1 – $F_{PFS}/F_{g.m.}$=1.65; 2 – $F_{PFS}/F_{g.m.}$=2.50; 3 – $F_{PFS}/F_{g.m.}$=3.35

With an increasing equivalent diameter of grains, up to a certain point, the efficiency of filter with VDE increases almost linearly. After passing the critical value $d_{g.m.2}/d_{g.m.1}$, at which parameter T_2/T_1 reaches a maximum value, the continued growth in the size of grains leads to a sharp decrease in efficiency. With an increase in the PFS filtration area a maximum extremum is implemented at a larger value of $d_{g.m.2}$. In Fig. 3 shows an example of calculation of dependence of the efficiency of application of VDE on the resultant surface area of $F_{PFS}/F_{g.m.}$ at different values of parameter η. Calculations are shown for $d_{g.m.2}/d_{g.m.1}=1.08$.

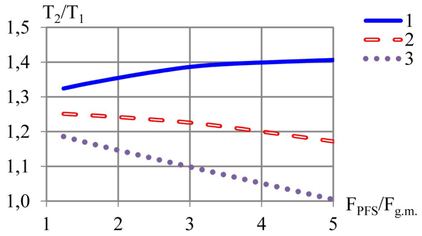

Fig. 3. Influence of the PFS surface area and parameter η on the operational efficiency of filter with VDE at constant value of $d_{g.m.2}/d_{g.m.1}$: 1 - η=0,05; 2 - η=0,1; 3 - η=0.15

With an increase in the number of VDE and, accordingly, the surface area of PFS if a longer washing of VDE is required, the efficiency of their application is reduced, if with the increasing number of VDE the size of grains in a granular filter layer does not change. This effect can be levelled off by selecting for each value of F_{PFS} the rational value of equivalent diameter of grains, at which parameter T_2/T_1 is maximal (Fig. 4).

The distribution of sediment layer at the surface of PFS for VDE height was analyzed (Fig. 5). Fig. 6 shows example of calculation of change in the distribution of water flow rate that passes through PFS over the filtering mode of filter operation for the height of VDE.

Fig. 5 shows that the thickness of the sediment layer at the surface of PFS has the greatest value at the top of VDE. At the bottom, along section (0,7 0,8)$h_{v.e.}$, sediment is virtually non-existent. Similarly, Fig. 6 shows that at the bottom part, no water inflow is observed through PFS. Flow rate $Q_{v.e.}$ practically does not change for the entire period of filtration.

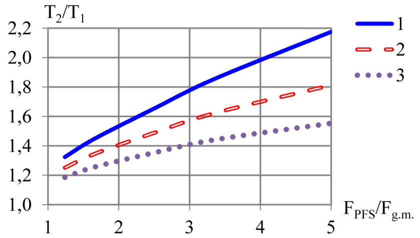

Fig. 4. Influence of the PFS surface area and parameter η on the operational performance of filter with VDE at a rational value of $d_{g.m.2}/d_{g.m.1}$: 1 – η=0.05; 2 – η=0.1; 3 – η=0.15

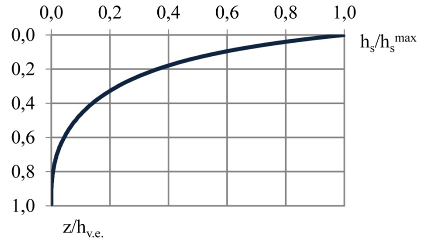

Fig. 5. Example of the calculation of sediment distribution for the height of VDE

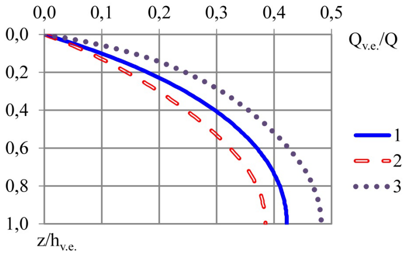

Fig. 6. Dynamics of distribution of water flow rate, filtered through PFS, for the height of VDE: 1 – t/T_2=0; 2 – t/T_2=0.5; 3 – t/T_2=1

It is logical to propose to exclude filtering through PFS along this section by making a partition impenetrable. This makes it possible to reduce the PFS area and decrease the amount of water for their washing.

Fig. 7 shows example of calculation of dependence of the efficiency of filter with VDE on its working height reduced to the thickness of a granular filter layer $h_{v.e.}/h_{g.m.}$. An increase in the working height of VDE leads to an increase in the efficiency of their utilization. When the value of parameter $h_{v.e.}/h_{g.m.}$ approaches a critical magnitude, the efficiency increases dramatically and reaches the maximum value. Next, the effect of VDE application drops smoothly.

To study load distribution on VDE and a granular filter layer, we calculated dynamics of flow rate passing through VDE over the filtering mode of filter operation at different values of the surface area of PFS F_{PFS}. In all calculations, for each value of F_{PFS}, we chose the rational values of equivalent diameter of grains in a granular filter layer. An example of such calculation is shown in Fig. 8.

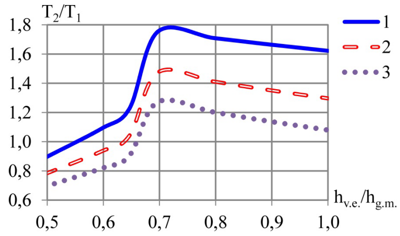

Fig. 7. Effect of the working height of VDE and parameter η on the operational performance of filter with VDE: 1 – η=0.1; 2 – η=0.2; 3 – η=0.3

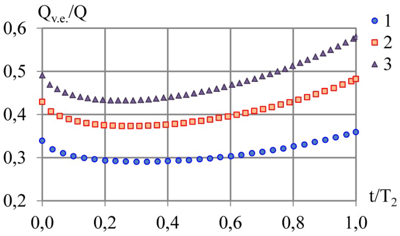

Fig. 8. Example of calculating the dynamics of water flow passing through VDE: 1 – $F_{PFS}/F_{g.m.}$=1.65; 2 – $F_{PFS}/F_{g.m.}$=2.50; 3 – $F_{PFS}/F_{g.m.}$=3.35

Data in Fig. 8 show that at the beginning of a filtering cycle, as a layer of sediment forms at the surface of PFS, consumption of water $Q_{v.e.}$, passing through VDE, decreases. Next, a granular filter layer colmatates, consumption $Q_{v.e.}$ again increases and, by the end of the filtering mode, reaches the maximum value. With an increase in the number of VDE and, accordingly, the surface area of PFS, the load on VDE increases, not linearly, but with attenuation.

6. Discussion of results or research into water purification at parallel filtration through a granular medium and a fibrous medium

The existence of a maximal extremum in the dependence $T_2/T_1(d_{g.m.2}/d_{g.m.1})$ (Fig. 2) can be explained as follows. At a parallel filtering through a granular filter layer and PFS VDE, part of the load is redistributed on PFS. Filtration speed in the lower layers of the granular layer decreases, transport of suspended solids slows down. The lower layers are underloaded. In this case, a criterion for disabling the filter for washing is the achievement of head losses limits. Therefore, an increase in the equivalent diameter of grains leads to an increase in the operational efficiency of filter with VDE: reduced pressure loss, with simultaneous acceleration of the transfer of suspended matter to the lower layers. With a further increase in parameter $d_{g.m.}$, at some point, a criterion for starting the regeneration is the "breakthrough" of contaminants into the filtrate. Further increase in the grain size of a granular filter layer leads to a sharp deterioration in the efficiency of VDE application.

An increase in the number of VDE and, accordingly, area of filtering through PFS, on the one hand, makes it possible to increase the load on PFS, on the other hand, leads to an increase in the volume of water required for washing. As a result, the increasing number of VDE leads to the attenuation in the growth of effectiveness or even worsening (Fig. 3, 4). It is possible to improve efficiency of VDE application as a result of the selection of a rational value for equivalent diameter of grains and reduction in the surface area of PFS by eliminating inefficient VDE zones (Fig. 7). As shown in Fig. 5, 6, this region is located at the bottom of VDE. Weak intensity of filtering through PFS in a given area is due to the low speed of filtering through a granular filter layer. In the lower layers of a granular filter, there is virtually no transit flow, these layers are less colmatated, and the remaining thickness of a granular filter layer does not create such large losses of head as a finely porous fibrous shell. The flow of water is redistributed in the direction of a granular filter layer, there is almost no inflow to PFS.

Consumption of water, which passes through PFS VDE, varies throughout the work of the structure under filtering mode (Fig. 8). At the beginning, sediment at the surface of PFS has a more significant impact on their throughput capacity: flow rate $Q_{v.e.}$ decreases. Next, the degree of colmatation of a granular filter layer grows, the flow of water passing through it is reduced accordingly, the flow rate through VDE increases. With an increase in the surface area of PFS, the rational value of equivalent diameter of grains also increases (Fig. 2). A granular layer consisting of larger particles passes water with less head losses, which helps increase the flow through a granular filter layer. As a result, despite an increase in area F_{PFS}, flow rate $Q_{v.e.}$ grows less intensively (Fig. 8).

The results of present research are qualitative in character. Their practical value is that they justify the possibility to improve work of the rapid filter by applying VDE with PFS. The regularities of influence of basic parameters on the operational performance of the structure were investigated. We show the existence of such values of these parameters at which efficiency is maximal. The robustness of data obtained is confirmed by the fact that parameters for the filter and a granular filter layer are taken within the range of existing structures. Calculations that employed the given mathematical model for the filter of traditional design demonstrated results that correlate with actual values for the duration of a filtering cycle. In order to obtain specific quantitative recommendations, it is required to conduct a further experimental study into physical-chemical properties of a particular filtered suspension. It is impossible now to solve this task theoretically. However, mathematical modeling can dramatically reduce the amount of experimental research.

To improve the reliability of results of theoretical research reported, it is planned in the nearest future to carry out a comparison with data on the experimental study of the device operation whose schematic is shown in Fig. 1.

In the future, we should consider filtering with a gradual blocking of pores in the porous shell. This would make it possible to extend the scope of application of the developed mathematical model, which takes into account only the formation of a sediment layer at the surface. The suspension captured by granular filters has a poly-dispersed structure, therefore it is impossible to completely exclude other types of filtration.

The regeneration of PFS requires a more thorough investigation. Duration and intensity of PFS washing have a significant impact on the efficiency of VDE application.

7. Conclusions

1. We presented a fundamental concept and basic operational principles of the rapid filter with a granular filter layer containing VDE with PFS. Such a solution makes it possible to increase the duration of work of a filtration structure without washing.

2. A mathematical model is constructed of water purification at the rapid filter containing VDE with PFS. A filtration equation was derived to describe parallel filtration of a low-concentrated suspension through a granular medium and a fibrous medium. This mathematical model makes it possible to calculate rational parameters of the device at which the efficiency of VDE application is maximal.

3. Using a mathematical model, we conducted numerical experiments. They showed that a significant impact on the operational efficiency of a filtering structure with VDE is exerted by the equivalent diameter of particles in a granular filter layer. The value of this parameter must be chosen in such a way as to prevent the “breakthrough” of contaminants into the filtrate. We also substantiated the expedience of excluding from the process of filtering an ineffective lower VDE zone (approximately 30 % by height). This reduces the extra amount of washing water required for the regeneration of PFS.

References

1. Zhurba M. G., Sokolov L. I., Govorova G. M. Water supply. Designing systems and structures. Vol. 2: textbook. 3rd ed., ext. and rev. Purification and conditioning of natural waters. Moscow: Publishing house of the Association of Construction Universities, 2010. 552 p.
2. Huck P. M., Sozanski M. M. Designing and Optimizing Drinking Water Treatment Processes – A Guide to Conducting Investigations. IWA Publishing, 2012. 200 p.
3. Grabovsky P. A., Larkina G. M., Progulny V. I. Washing of water purification filters. Odessa: Optimum, 2012. 240 p.
4. Theoretical basis of water purification / Kulikov N. I., Naimanov A. Y., Omelchenko N. P., Chernyshev V. N. Donetsk: Publishing house Nouvelage (Donetsk branch), 2009. 298 p.
5. Gurinchik N. A. Investigation of the influence of the composition of a media of a contact clarifier using a mathematical model // Municipal economy of cities. 2014. Issue 114. P. 105–108.
6. Stacked Rapid Sand Filtration / Adelman M., Liu M., Cordero A., Ayala J. // Cornell University, 2010. URL: https://confluence.cornell.edu/display/AGUACLARA/Stacked+Rapid+Sand+Filtration+Summer+2010+Reflection+Report+1
7. Karahiaur A. S., Volkov V. N. Mathematical modeling of the operation rapid filter with the bypass of part of the flow to the lower layers // Scientific Bulletin of Civil Engineering. 2017. Vol. 90, Issue 4. P. 180–187.
8. Schevchuk O. O. Mathematical description of multistage filtration // Filtration and Separation: the 2nd European Conf. Compiegne, 2006. P. 259–265.
9. Pabolkov V. V. Improvement of the work of rapid filters of water treatment facilities during preparation of drinking water: author’s abstract. dis. ... PhD. Kharkiv: KhNUCA, 2015. 20 p.

10. Effect of filtration rate on coal-sand dual-media filter performances for microalgae removal / Sabiri N.-E., Monnier E., Raimbault V., Massé A., Séchet V., Jaouen P. // Environmental Technology. 2016. Vol. 38, Issue 3. P. 345–352. doi: 10.1080/09593330.2016.1193224
11. Pilot study of low-temperature low-turbidity reservoir water treatment using dual-media filtration with micro-flocculation / Zhang G., Kang X., Zhang P., Zeng G. // 2011 International Conference on Multimedia Technology. 2011. doi: 10.1109/icmt.2011.6002915
12. Odira P. M. A., Ndiba P. K. Performance of Crushed Coconut Shell Dual Media Filter // Journal of Civil Engineering Research and Practice. 2007. Vol. 4, Issue 2. doi: 10.4314/jcerp.v4i2.29176
13. Determination of head loss progress in dual-media BOPS-sand filter using numerical modeling incorporated with matrix approach / Jusoh A., Rajiah M. N. A., Nora'aini A., Azizah E. // Desalination and Water Treatment. 2011. Vol. 32, Issue 1-3. P. 33–41. doi: 10.5004/dwt.2011.2675
14. Sanyaolu B. O. Comparative performance of a charcoal dual media filter and a conventional rapid sand filter // Journal of Natural Sciences Engineering and Technology. 2010. Vol. 9, Issue 1. P. 137–146.
15. Soyer E. Performance comparison of granular media filter beds // Desalination and Water Treatment. 2016. Vol. 57, Issue 52. P. 24867–24881. doi: 10.1080/19443994.2016.1150206
16. Schöntag J. M., Sens M. L. Effective production of rapid filters with polystyrene granules as a media filter // Water Science and Technology: Water Supply. 2015. Vol. 15, Issue 5. P. 1088–1098. doi: 10.2166/ws.2015.072
17. Gawade S., Misal S. Analysis of PVC rapid sand filter // Imperial Journal of Interdisciplinary Research. 2016. Vol. 2, Issue 9. P. 1370–1373.
18. Bugay N. G., Krivonog A. I., Krivonog V. V. Contact reagent purification of water by filters of fibrous-porous polyethylene // Applied hydromechanics. 2007. Vol. 9, Issue 1. P. 8 22.
19. Improving the efficiency of filter structures using drainage systems made of porous polymer materials / Epoyan S., Karahiaur A., Volkov V., Yarkin V. // MOTROL. Commission of motorization and energetics in agriculture. 2016. Vol. 18, Issue 6. P. 102–109.
20. Polyakov V. L. Filtration of a suspension with variable content of suspended particles through a uniform filter medium at a nonlinear mass-exchange kinetics // Reports of the National Academy of Sciences of Ukraine. 2009. Issue 12. P. 61–68.
21. Mathematical modeling of the operation of rapid filters / Noskov M. D., Zaytseva M. S., Istomin A. D., Lukashevich O. D. // Vestnik of TSUAB. 2008. Issue 2. P. 126–138.
22. Shilin B. I., Ulianov A. A. Development of porous structure model of fibrous materials of filters of volumetric type for clearing of surface water // Biospheric compatibility: human, region, technologies. 2016. Issue 4 (16). P. 71–78.
23. Nabovati A., Llewellin E. W., Sousa A. C. M. A general model for the permeability of fibrous porous media based on fluid flow simulations using the lattice Boltzmann method // Composites Part A: Applied Science and Manufacturing. 2009. Vol. 40, Issue 6-7. P. 860–869. doi: 10.1016/j.compositesa.2009.04.009
24. Using polymeric shells of the drainage systems of rapid filters for tertiary treatment / Volkov V. M., Epoyan S. M., Karahiaur A. S., Babenko S. P. // Municipal economy of cities. 2017. Issue 139. P. 135–142.
25. Oleynik A. Ya., Tugay A. M. Modeling of the processes of colmatage and suffosion in the filter zone of wells // Reports of the National Academy of Sciences of Ukraine. 2001. Issue 9. P. 190–194.