UDC 628.16
DOI: 10.15587/1729-4061.2017.109841

A SIMULATION STUDY OF SURFACE WATER PURIFYING THROUGH A POLYSTYRENE FOAM FILTER

S. Martynov
PhD, Associate Professor*
E-mail: s.y.martynov@nuwm.edu.ua
S. Kunytskyi
PhD
Research Department**
E-mail: s.o.kunytskiy@nuwm.edu.ua
A. Orlova
PhD, Associate Professor*
E-mail: a.m.orlova@nuwm.edu.ua
*Department of Water Supply, Drainage and Drilling**
**National University of Water and Environmental Engineering
Soborna str., 11, Rivne, Ukraine, 33028

Вдосконалено математичну модель очищення поверхневих вод на фільтрах з пінополістирольним завантаженням та проведено порівняльний аналіз роботи фільтрів з однорідним та неоднорідним завантаженням при фільтруванні води в різних напрямках. Проведено статистичну обробку результатів дослідження з встановленням адекватності та можливості застосування для математичного опису водоочисних процесів

Ключові слова: пінополістирольне завантаження, тривалість фільтрування, втрати напору, концентрація забруднення, гранулометричний склад

Усовершенствованная математическая модель очистки поверхностных вод на фильтрах с пенополистирольной загрузкой и проведен сравнительный анализ работы фильтров с однородной и неоднородной загрузкой при фильтровании воды в разных направлениях. Проведена статистическая обработка результатов исследования с установлением адекватности и возможности применения для математического описания водоочистных процессов

Ключевые слова: пенополистирольная загрузка, продолжительность фильтрования, потери напора, концентрация загрязнений, гранулометрический состав

1. Introduction

The process of sustainable development of society is impossible without providing people with drinking water of appropriate quality. Experts prove that poor-quality water causes diseases of the blood-vessel system and the intestinal tract [1]. Therefore, a vital problem is to extract and supply water of appropriate quality [1, 2]. The processes of water preparation for both economic and drinking needs of the population and manufacturing needs of industrial enterprises require bringing the physical and chemical properties of water in compliance with regulatory requirements [3]. Various technological workflows are used for this purpose. The choice of a technological scheme of water purification is based on the physical and chemical indicators of the water quality of a natural source. However, it is also necessary to take into account the characteristics of pollutants and the requirements of consumers to water quality, the efficiency of treatment facilities, etc.

Surface water often contains suspended substances, characterized by significantly specific color and having a particular smell and taste. Such impurities worsen the physicochemical parameters of water, so they should be eliminated before transporting water through the water supply network.

The choice of a method of water preparation is based on studying water quality indicators of the water source (the chemical composition of water) obtained as a result of physicochemical, sanitary-bacteriological and technological analyses and with regard to a number of other indicators. Reagent methods of water purification and discoloration are used most often for cleaning surface water from coarse dispersed, colloidal and other contaminants. The main units in such methods are filtering facilities [1, 4, 5], whose efficiency depends not only on the quality of treated water but also on the operation cost.

Filtering structures can be represented by fast filters or contact lighteners [4]. In order to reduce the cost of constructing and operating surface water purification stations, it is necessary to establish correctly the design and technological parameters of the filtering structures. This problem can be solved using mathematical modeling.

2. Literature review and problem statement

The problems of research [6–23] on water filtration can be divided into several directions.

The first direction of research includes devising new principles of water purifying by filtration and improving the work of separate units and elements of water purification structures [6–9]. A separate identifiable direction is research on applying various methods of preliminary water preparation in order to increase the effectiveness of contaminants' suspension and the density of sediment accumulation in the pore space of filters [1, 11].

To increase the dirt load capacity, filtration is used in the direction of reducing the grain size, which ensures an even distribution of pollution in terms of the loading height and lower pressure losses.

Another area of research to improve the efficiency of water purification by granular filters is the search for materials with high porosity and specific surface [9, 12, 13].

Natural and artificial materials are used as grain loading of filters [1, 2, 4]. The type of filter loading, the grain parameters and the height of the loaded layer greatly affect the efficiency of water purification, the size of the filter plants and their performance [6–13].

One of the economically feasible loads is a floating material, in particular, polystyrene foam, which has a number of technical and economic advantages, compared to other materials [7, 10, 12].

Granulated expanded polystyrene (EPS) is made of the polystyrene product by processing it through hot water or steam. The commodity polystyrene is of the brands EPS-s (soluble), EPS-b (bound), and EPS; it is manufactured in the form of spherical particles, colorless or light-white. Large fractions of polystyrene can be crushed prior to foaming and then foamed. Such granules are called shredded expanded polystyrene. Expanded polystyrene (or polystyrene foam) loading can be single-layer or double-layer [1, 10].

Among the directions of research on intensifying the work of filtering structures, it is necessary to highlight the development of improved mathematical models and methods of calculation, and, first of all, the use of computer technologies [14–16, 18, 19].

On the basis of experimental studies, a significant number of dependencies are proposed for heavy (sand, claydite, anthracite, etc.) and floating (expanded polystyrene) loads, which integrate the basic parameters of filters – the speed of filtration, the diameter of the loaded grains, the height of the layer, and the input concentration of pollutants [1, 10, 20]. However, such dependencies can be used under limited conditions for preliminary selection of structural parameters of filters, and they are of low predictive value.

Mathematical models of surface water purification through fast filters are mainly developed for “heavy” loads and include equations on the balance of matter and the process kinetics as well as a set of equations for determining pressure loss [14, 17, 20].

To describe the kinetics of the process, a large number of equations can be divided into linear and nonlinear, which take into account separation of previously adhered particles and their inseparability [2, 15, 18].

Among the well-known theories of the process of water purifying by filtration, the most widely recognized theory is filtration of low-concentration suspensions, described in [17]. According to this theory, the filtering process through fast filters has a physicochemical nature. The effect of the water lightening is related to suspended particle sticking to the sand grains under the influence of the van der Waals intermolecular forces of attraction. However, the mathematical model proposed in [17] can be used under limited conditions, with constant parameters of the filtering and properties of the porous medium; it partly disregards the granulometric composition of the load and does not take into account changes in the kinetic coefficients throughout the loading height. Such a simplified approach is associated with the complexity of obtaining analytical decisions. It should be noted that the diversity of the physicochemical indicators of surface water quality and methods of pre-treating such water requires conducting pilot field studies to determine the kinetic coefficients of the mathematical model.

Further development of mathematical models of water purification should be based on the interaction of hydraulic and physicochemical processes in water filtration, changes in the hydraulic properties of the medium, the non-stationary nature of the purification process, different models of mass transfer kinetics, peculiarities of the effect produced by the properties of the formed medium, and the like.

Filters with expanded polystyrene loading, which were first proposed to be used for water purification at the Department of Water Supply and Drilling, Ukrainian Institute of Water Economy Engineers (now National University of Water Management and Nature Resources Use), are widely employed worldwide [4, 12, 13]. In this regard, for a reasonable choice of optimal structural and technological indicators of work, there is a need to develop a mathematical model that would take into account the peculiarities of such filters’ operation.

3. The aim and objectives of the study

The aim of the study is to improve the mathematical model of surface water purification, to adapt it to float (expanded polystyrene) loading and to conduct a comparative analysis of filters with homogeneous and non-uniform loads when filtering water in different directions.

To achieve the aim, the following objectives are set:

– to improve the mathematical model of water lightening through a polystyrene foam filter, which would take into account the interaction of hydraulic and physicochemical processes during filtering of water by a filter with expanded polystyrene, the change in the hydraulic properties of the medium, the unsteadiness of the process of purification, and the peculiarities of the influence of the properties of the formed medium; it would additionally help take into account the granulometric composition of the loading, the filtration direction, changes in the kinetic coefficients of adhesion, particle separability, and porosity throughout the height of the load;

– to specify, on the basis of test results, the kinetic coefficients of particle adhesion and separation in the mathematical model of water purification through contact polystyrene foam filters;

– to conduct a comparative analysis of the work of polystyrene foam filters under different conditions;

– to determine the optimum height of loading for polystyrene foam filters by the example of treating water of the Horyn River (Ukraine) for drinking needs.

4. Materials and methods for studying the process of purifying surface water through a polystyrene foam filter

In the theory of filtering low concentric suspensions, it is common to consider two main parameters that can help determine when a filter should be washed – the time of reaching the critical pressure loss and the protective action time of the load [2, 4, 10, 15–18, 21, 23, 24].

The duration of the protective action of the load is the time during which the filtering load can purify water to a specified quality level. For heavy loading, in [13, 23] the duration of protective action is determined by the formula:

$$t_{protect}=\frac{1}{K}\left[\frac{h}{v^{1.7}\cdot d^{0.7}}-\frac{S_0\cdot d}{v}\right], \tag{1}$$

where K is the parameter obtained according to experimental results; h is the thickness of the filtering layer; S_0 is a constant that depends on the given ratio of the turbidity of water entering the purification process C_0 to the turbidity of the filtrate C_f.

An option is possible when the filter is flushed not due to the deterioration of the filtrate quality but due to a critical pressure loss. In this case, the length of the filter cycle for heavy loads can be determined by the formulae [4, 17, 21, 23]:

$$t_{pressure}=\frac{P_{cr}-P_0}{P_0\cdot f(A)}\cdot\frac{b}{a}X, \tag{2}$$

$$t_{pressure}=\frac{1}{\gamma\cdot\phi_1\sqrt{d_e}}\left(\frac{P\cdot d^2}{\phi_0\cdot v}-x\right), \tag{3}$$

where P_{cr} and P_0 are the critical and initial pressure losses in the filter; x is the thickness of the filtering layer of the loading;

$$f(A)=\frac{h}{t}\cdot\frac{b}{a\cdot i_0}, \tag{4}$$

where h/t is the rate of the pressure loss increase; i_0 is the hydraulic incline in the clean filter loading; a and b are filtering parameters; γ is the coefficient that takes into account the influence of the physicochemical properties of water and sediment, the concentration of sediment in the source water and the filtrate, the initial porosity of the loading and the structural characteristics of the sediment; ϕ_1 is the coefficient taking into account the degree of the load heterogeneity; ϕ_0 is the coefficient that depends on the viscosity of water, porosity of the granular layer and the form of the grains in the loading; and P is a pressure.

Formula (3) makes it possible to calculate the duration of the work of grainy filters until the deterioration of the filtrate quality. This equation can be used to calculate a heterogeneous granulometric composition that is homogeneous by the type of the filter loading material – when the parameters of the described process are determined by the equivalent diameter of the filter medium.

The duration of the filter work is affected by several factors [2, 4, 17, 23], namely:

a) the filtration velocity, determined according to the formula [23]:

$$T=\frac{P-S_1\cdot v}{k_1\cdot S_1\cdot v^2}, \tag{5}$$

according to formula (5), with increasing the filtering speed, the duration of the filter operation is sharply reduced;

b) the grain size of the filtering load, determined by the formula [4]:

$$T=\frac{P-S_1\left(\frac{d_1}{d_2}\right)^2 v}{k_1\cdot S_1\left(\frac{d_1}{d_2}\right)^2 v^2}. \tag{6}$$

Formula (6) helps determine the duration of filter work with a filter load having a grain diameter d_2 if the duration of filter work is known for a filter load having a diameter d_1. The analysis of the formula shows that an increase in the grain diameter of the filter material increases the duration of the filter work. This provision reflects the theoretical basis for the tendency to increase the grain size of loading for fast filters.

The foregoing formulae (1)–(6) were developed for heavy granular materials; their use for polystyrene foam loading requires labor-intensive determination of a number of experimental coefficients and dependencies. In addition, they do not make it possible to simulate the work of grainy filters in dynamic conditions; therefore, a simplified approach is assumed to describe non-uniform loading.

Using the criterion equations that relate the time of the protective action of the load and the time of reaching the critical pressure loss to the main factors (physicochemical composition of water, loading height, water turbidity, filtering speed, and properties of the adhered sludge), mathematical dependences have been developed. The experimental data on purifying surface water through polystyrene foam filters using the method of selected points helped suggest dependences (7) and (8) [4, 17, 21] to determine the following:

– the protective action time of the load:

$$t_{protection}=\frac{B\cdot L}{(M\cdot V)\cdot\sqrt[3]{d}}, \tag{7}$$

– the time of reaching the critical pressure loss:

$$t_{pressure}=\frac{5\cdot d^2}{N\cdot M^2\cdot\sqrt{V}}(P_{fin}-P_0), \tag{8}$$

where W is the coefficient characterizing the physicochemical properties of water; L is the height of the loaded layer, m; M is the water turbidity, mg/dm^3; V is the filtration velocity, m/h; N is the coefficient of strong properties of the sediment; d is the diameter of the load granules, mm; P_{fin} and P_0 are the final and initial pressure losses, m.

However, the last two equations – (7) and (8) – also do not make it possible to study the process of water purification through a polystyrene foam filter in dynamic conditions and do not take into account the heterogeneity of the loading. Therefore, there is a need to improve these models.

5. Results of the research to improve the mathematical model

The surface water purification process through a polystyrene foam filter was carried out using a mathematical model represented by equations (9)–(15). This model was solved numerically by the method of longitudinal-transversal dispersion. To do this, an algorithm was developed and a program was written in the MathCAD environment. The coefficients of the model (α, β, γ) were identified in MathCAD on the basis of the results of experimental studies of purifying water of the Horyn River, Rivne Oblast (Ukraine), using the Minimize function. The selected water body has a physicochemical composition of water similar to most of the average plain rivers in Ukraine. The criterion for finding the optimal values of the coefficients was the minimum value of the sum of the difference between the squares of the experimental values (the concentration of suspended substances in the filtrate and the pressure loss in the polystyrene foam charge) and the calculated values obtained by mathematical model (11)–(15).

After determining the coefficients of the model (α, β, γ), simulation was performed under different initial parameters. The results were summarized and presented in the form of graphs with corresponding conclusions.

The advanced mathematical model consists of two interdependent blocks – water lightening (equations (9)–(12)) and hydrodynamic (equations (13)–(15)).

The equation on the material balance can be represented by the differential equation:

$$V\cdot\frac{\partial C(x,t)}{\partial x}+\frac{\partial\rho(x,t)}{\partial t}=0, \tag{9}$$

where V is the velocity of filtration, m/h; $C(x,t)$ is the concentration of suspended substances, g/m^3, which varies with the height of loading and over time; x is the coordinate on the height of the loaded layer, m; t is the filtration time, h; $\rho(x,t)$ is the sediment density in the loaded layer, g/m^3.

In equation (9), unlike in the model presented in [17], the sediment density in the loaded layer is taken loose for the entire loaded layer, and it varies throughout its height and over time.

To describe the kinetics of the water purification process in the polystyrene foam layer, the following equation can be used:

$$\frac{\partial C(x,t)}{\partial x}=a(x)\cdot\rho(x,t)-b(x)\cdot C(x,t), \tag{10}$$

where $a(x)$ and $b(x)$ are kinetic coefficients characterizing the intensity of contaminants' separation from and adhesion to the loaded grains and determinable by the formulae obtained using the dimension theory [21, 23]:

$$a(x)=\alpha\cdot V^{\varepsilon 1}\cdot d(x)^{\varepsilon 2} \tag{11}$$

and

$$b(x)=\beta\cdot V^{\varepsilon 3}\cdot d(x)^{\varepsilon 4}, \tag{12}$$

where α and β are empirical coefficients that depend on the quality and method of reagent preparation of water; ε_1, ε_2, ε_3, and ε_4 are coefficients that respectively make up 1.0; –1.0; –0.7; and –1.7 [4]; $d(x)$ is the diameter of the loaded grains, mm, with the load varying in its height.

Equation (10) is represented by the linear kinetics of mass transfer taking into account separation of previously adhered particles. In equations (10)–(12), unlike in the model presented in [17], changes in the kinetic coefficients $a(x)$ and $b(x)$ in the load height and the inhomogeneity of the loading are taken into account. The nature of changes in the diameters of the loaded grains throughout the layer height can be set on the basis of experiments on real loads or taken as a mixture of them for choosing the optimal variant in terms of the best quality of the filtrate during the filter cycle or the minimum flow of needed water, depending on the specific modeling conditions.

The hydrodynamic unit is described by the equations of changes in the hydraulic slope, the load porosity, and total pressure loss.

The hydraulic inclination of the loading for various hydraulic modes of operation is conveniently determinable by the well-proven Kozeny-Carman equation:

$$I=\frac{V\cdot\nu(T)}{0.0055}\cdot\left(\frac{\alpha^{*}}{d(x)}\right)^{2}\cdot\frac{\left(1-m(x,t)\right)^{2}}{m(x,t)^{3}}, \tag{13}$$

where $m(x, t)$ is the porosity of the loaded layer, which varies with the height of the load and over time; α^* is the coefficient of the grain form; $\nu(T)$ is the kinematic coefficient of water viscosity, m^2/s, which depends on the water temperature T.

To take into account the change in the loading porosity during water filtration, the used formula is the following:

$$m(x,t)=m(x,0)-\rho(x,t)/\gamma, \tag{14}$$

where $m(x,0)$ is the initial porosity of the loaded layer; γ is the mass concentration of solids per unit volume of sediment, g/m^3.

In equations (13) and (14), unlike in the model shown in [17], the load porosity varies depending on the layer height and the duration of filtering.

The filtering of water through the filter load is carried out under the difference in pressures at the inlet and outlet of the filter. This difference in pressures is commonly referred to as a loss in pressure in the filter loading.

Total pressure loss in the polystyrene foam loading can be determined by the formula:

$$P_{total}(t)=\int\limits_{x=0}^{x=L} I(x,t)\,d(x), \tag{15}$$

where L is the total height of the filter load, m.

Equation (15) allows determining the dynamics of the pressure loss throughout the loading, depending on the granulometric composition.

The improved mathematical model represented by equations (9)–(15) is solved under the following initial and critical conditions:

– at $x=0\rightarrow C=C_0$;
– at $t=0\rightarrow\rho=0$;
– at $x=L\rightarrow C\leq C_{cr}$;
– at $t=t_f\rightarrow P_{protect}\leq P_{adm}$;
– at $t\rightarrow\infty\rightarrow\partial C/\partial x=0,\ C=C_0,\ \rho=\rho_{cr}$,

where C_0 is the concentration of suspended substances at the inlet of the polystyrene foam loading, mg/dm^3;

C_{cr} is the maximum permissible concentration of suspended matter in the filtrate.

According to the current standards of Ukraine, the C_{cr} should not exceed 0.58 mg/dm^3;

t_f is the standard duration of filtering. According to the "Rules of technical operation of water supply and drainage systems of settlements of Ukraine", the duration of the filter cycle should not exceed 2 days;

P_{adm} is the maximum admissible pressure loss in the polystyrene foam loading. According to [4, 21, 24], a pressure loss in polystyrene foam filters with upward filtration is recommended to be 2.0...2.5 m.

The critical saturation of the porous space with suspended sludge during the simulation was taken to be equal to the density of the sediment with a decrease in the load porosity down to 0.2.

To solve the aforementioned improved mathematical model, the given parameters are the following: the distribution of grain diameters throughout the height of the loading; the porosity of the initial clean loading; the empirical coefficients α and β; the mass concentration of solid particles; the filtration velocity; the input concentration of suspended substances and, if necessary, the filtration duration and the maximum pressure loss.

6. Discussion of the results of studying and testing the improved model on natural river water

The mathematical model (9)–(12) of surface water purification through filters with polystyrene foam loading has been improved and a comparative analysis of the filters operation under different conditions has been carried out. Approbation of the improved model was performed on the surface water of the Horyn River (Rivne Oblast, Ukraine). The structure of the surface water of the mentioned object is similar to the physicochemical composition of water of most surface rivers of Ukraine.

The simulation was carried out for water purification of the Horyn River from suspended matter in a one-stage scheme with contact polystyrene foam filters, which involved introduction of reagents, a mixer and ascending filtration through the polystyrene foam filters [1, 23].

On the basis of experimental studies presented in [4, 21, 23], the obtained values were determined as follows: the kinetic coefficients $\alpha=1.7\cdot10^{-5}$ and $\beta=5\cdot10^{-4}$ $m^{2.7}/h^{1.7}$; the sediment density γ=34,000 kg/m^3; the particle separation coefficient $a=0.123$ h^{-1}; the particle adhesion coefficient $b=12.3$ h^{-1} by the method shown in section 4.

In Fig. 1, the solid line shows the results of calculating according to the mathematical model, whereas the dotted line shows the experimental data. The latter confirm the calculation results (obtained on the basis of the mathematical model (9)–(15)), and the relative error is 4...9 %, which is determined according to the standard criteria for statistical processing of the research data.

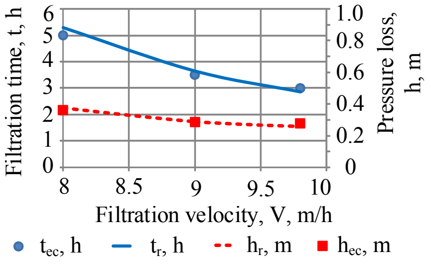

Fig. 1. The dependence of the optimal filtration time (*t*) and the corresponding pressure loss (*h*) on the filtration velocity (*V*)

With the use of the improved mathematical model (9)–(15), it was possible to obtain graphs of the concentrations of contaminants in the loaded layers over time (Fig. 2).

The graphs in Fig. 2, *a*, *b* differ only in the angle of inclination of the isolines to the abscissa axis – with increasing filtration velocity, there is a deeper penetration of contaminants into the load.

Fig. 3 shows the results of calculating the dependence of the filtration time on the filtration velocity for a homogeneous loading with a grain diameter of 1.4 mm, a loading height of 1.0 m and a concentration of suspended substances at the inlet to the loading of 78 mg/dm^3.

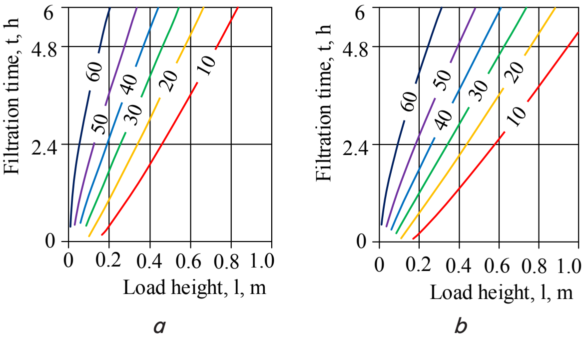

Fig. 2. The graphs of the isolines of concentrations of contaminants (mg/dm^3) in the loaded layers throughout the height (*l*) and over time (*t*) at: *a* – the movement of water through the loading at a speed of V=8 m/h; *b* – the movement of water through the loading at a speed of V=9 m/h

Consequently, the protective action time of the charge ($t_{protect}$) increases from 0.55 h to 21.55 h with a decrease in the filtering velocity from 10 m/h to 3 m/h by nonlinear dependence. At a filtering speed of 5 m/h, the protective action time of the load is 8.05 hours; therefore, the number of filter cycles per day will be 3. The loss of pressure in the polystyrene foam charge at reaching the protective action time varies in the range from 0.27 m to 0.74 m. This is due to the full saturation of the pore space of a smaller number of elementary layers of the loading.

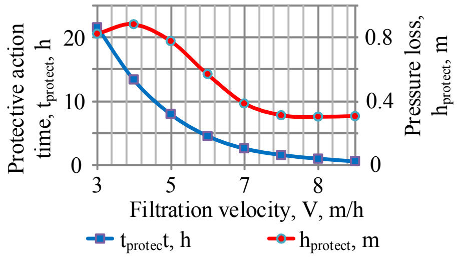

Fig. 3. The dependence of the protective action time ($t_{protect}$) of a homogeneous loading and the corresponding pressure loss ($h_{protect}$) on the filtration velocity (*V*)

Fig. 4 shows the graph of the isolines of pollution concentrations in time and throughout the loading height at V=5 m/h. Thus, at the beginning of the filtration, the concentration of suspended substances decreases to 10 mg/dm^3 after 20 cm of loading, and after 12 hours of operation, this height increases to 0.85 m.

In practice, non-uniform loading is used, which should be taken into account during simulation. Let us simulate the work of the contact polystyrene foam filter with the following loading parameters: d_{min}=0.9 mm, d_{max}=2 mm, d_{10}=1.01 mm, d_{80}=1.78 mm, FIN_P=1.76, d_E=1.4 mm, $h_{protect}$=1.0 m and a linear change in the grain diameters throughout the loading height.

For the above parameters, the dependence of the filtration duration on the filtration velocity and the corresponding pressure loss in the loading for ascending and descending filtration directions are shown in Fig. 5.

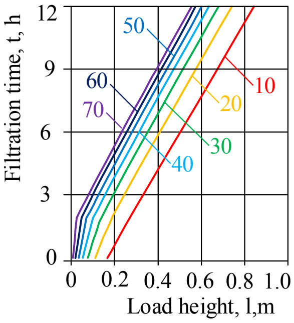

Fig. 4. The graph of the isolines of pollution concentrations (mg/dm^3) in the layers of a homogeneous loading throughout its height (l) and over time (t)

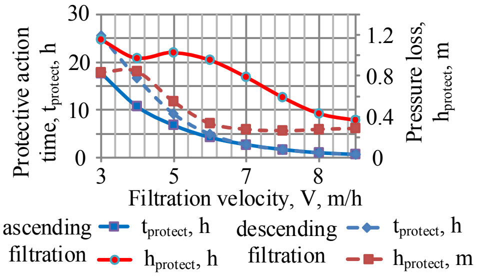

Fig. 5. The dependence of the protective action time of a non-uniform loading ($t_{protect}$) and the corresponding pressure loss ($h_{protect}$) on the velocity and direction of filtration (V)

In the improved mathematical model, the expansion of the loaded layer at higher filtration velocities in the downward direction was not taken into account. At a filtering speed of less than 6 m/h, the protective action of the load in the downstream filtering is greater than that of the ascending direction, and a lower pressure loss was observed in the downstream filtering. According to the graphs in Fig. 6, 4, in a homogeneous load, the protective action time of the load was approximately 8 hours, and in the non-uniform load, it was 6.8 hours, i. e. 15 % less. To ensure the duration of the protective action of the load for 8 hours, it is necessary to increase the height of the non-uniform loading by 30 %.

The results of calculating the optimal filtration time and the height of the polystyrene foam loading with ascending filtering are shown in Fig. 6 at the following parameters:

– the concentration of suspended substances in the filter – 78 mg/dm^3;

– the concentration of suspended substances in the filtrate – 0.58 mg/dm^3;

– the filtration velocity – 5 m/h;

– the diameter of the load grains – 0.8...1.2 mm;

– the critical pressure loss in the loaded layer – 0.9 m.

As the loading height increases, the time to achieve the protective action of the load increases and the time to reach the critical pressure loss [1, 4, 10, 15, 17–21, 23–25] is reduced. The optimum loading height is 1.0 m (Fig. 6), which was determined based on the equality of the time of the protective action of the load and the time to reach the critical pressure loss. Meanwhile, the filtering time is about 12 hours.

Fig. 7 shows the dependence of changes in the time of the protective action of the load and of the time of reaching the critical pressure loss on the filtration velocity.

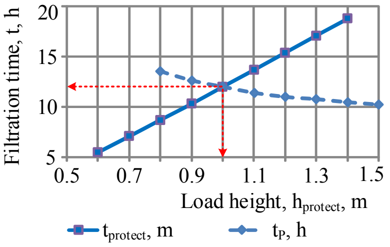

Fig. 6. The optimal filtration time determined at: C_0=78 mg/dm^3; V=5 m/h, d=0.8...1.2 mm, h_{cr}=0.9 m

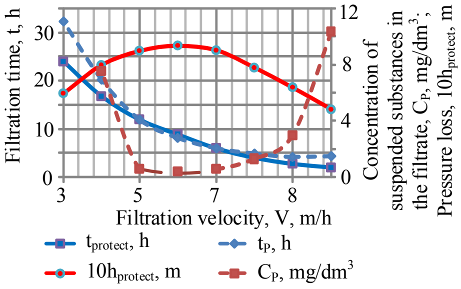

Fig. 7. The dependence of the protective action time of the loading ($t_{protect}$) and the time of reaching the critical pressure loss ($h_{protect}$) on the filtration velocity (V) at: C_0=78 mg/dm^3; $h_{protect}$=1.0 m, d=0.8...1.2 mm, h_{cr}=0.9 m, C_F=0.58 mg/dm^3

Consequently, $t_{protect}$ and t_P decrease as the filtration velocity increases. In the range of speeds 5...7 m/h, there is an approximate equality of $t_{protect}$ and t_P. An increase in the filtration velocity from 5 m/h up to 7 m/h provides the required degree of water purification. In this case, the filter cycle will decrease from 12 h down to 6 h, which corresponds to the current normative documents of Ukraine [3, 26]. If the filtration velocity deviates to a smaller or larger value, a gradual excess of $t_{protect}$ and t_P is observed, which requires additional analysis. In such cases, the filters are switched to the flushing mode.

With a filtration velocity of 6 m/h, the best efficiency of water purification is observed when reaching the critical pressure loss at 0.9 m. At the same speed, the greatest loss of pressure is observed when the protective action time of the load is reached. This is due to the smallest concentration of suspended matter in the filtrate and to the largest accumulation of contaminants in the pore space of the loading during the filter cycle.

7. Conclusion

1. The improved mathematical model of water purification through a polystyrene foam filter, consisting of water lightening (purifying) and hydrodynamic blocks (equations (9)–(15)), makes it additionally possible to take into account the granulometric composition of the loading, the direction of filtration, changes of the kinetic coefficients of adhesion, the particle separation and the porosity throughout the height of the load. The use of this model helps determine more accurately the effectiveness of detaining pollutants in the load and establish the structural and technological performance of the filters.

2. The advanced mathematical model has been solved numerically by the method of longitudinal-transversal disper-

sion. To do this, an algorithm was developed and a program was written in the MathCAD environment. The coefficients of the model (α, β, γ), which determine the kinetics of the particles' suspension and separation and affect the current loading porosity, were specified with the use of experimental data on purifying water of the Horyn River through a polystyrene foam filter in MathCAD using the Minimize function. The criterion for finding the optimal values of the coefficients was the minimum value of the sum of the difference in the squares of the experimental and calculated values (obtained with the improved mathematical model).

3. A comparative analysis of the work of filters with homogeneous and non-uniform loads was carried out. It has been found that in a non-uniform loading, the protective action of the load is 15 % less than in a homogeneous loading. To ensure an identical duration of the protective action of the load, the height of the non-uniform loading should be 30 % higher than for a homogeneous loading. Failure to consider the mathematical modeling of grains distribution throughout the load height results either in underestimated values of the required loading height and, consequently, an inadequate effect of water purification or in a reduced duration of the filtering, which increases the cost of the purified water.

4. It has been established that in the range of the filtration velocity of 5...7 m/h, there is an approximate equality between t_{protect} and t_{P}. Meanwhile, the required degree of water purification is provided. However, the duration of the filtering is reduced by half.

5. It has been determined that for the work conditions of the polystyrene foam filter, which were considered above, at the filtration velocity of 6 m/h, the best efficiency of water purification is observed when reaching the critical pressure loss at 0.9 m. At the same speed, the greatest loss of pressure is observed at reaching the protective action time of the load. This is due to the smallest concentration of suspended matter in the filtrate and to the largest accumulation of contaminants in the pore space of the load during the filter cycle.

References

1. Orlov, V. Energy saving in water treatment technologies with polystyrene foam filters [Text] / V. Orlov, S. Martynov, S. Kunytskiy // Journal of Water and Land Development. – 2016. – Vol. 31, Issue 1. doi: 10.1515/jwld-2016-0042
2. Mel'cer, V. Z. Fil'troval'nye sooruzheniya v kommunal'nom vodosnabzhenii [Text] / V. Z. Mel'cer. – Moscow: Stroyizdat, 1995. – 176 p.
3. Derzhavni sanitarni normy i pravyla. Hihienichni vymohy do vody pytnoi, pryznachenoi dlia spozhyvannia liudynoiu: DSanPiN 2.2.4-171-10 [Text]. – Kyiv, 2010.
4. Orlov, V. O. Ochyshchennia pryrodnoi vody na pinopolistyrolnykh filtrakh [Text] / V. O. Orlov, S. Yu. Martynov, A. M. Orlova et. al.; NUVHP. – Rivne, 2012. – 172 p.
5. Żurek, A. Environmental flow as an area of potential conflict between the role of groundwater in the supply and its environmental function [Text] / A. Żurek // Acta Scientiarum Polonorum Formatio Circumiectus. – 2015. – Vol. 13, Issue 4. – P. 301–314. doi: 10.15576/asp.fc/2014.13.4.301
6. Ying, Y. Recent advances of nanomaterial-based membrane for water purification [Text] / Y. Ying, W. Ying, Q. Li, D. Meng, G. Ren, R. Yan, X. Peng // Applied Materials Today. – 2017. – Vol. 7. – P. 144–158. doi: 10.1016/j.apmt.2017.02.010
7. Denisov, S. E. Analysis of the Effectiveness of Sorption and Membrane Technologies and Water Purification Equipment with Increased α-Activity for Domestic Water Supply [Text] / S. E. Denisov, M. V. Shirokova // Procedia Engineering. – 2016. – Vol. 150. – P. 2364–2368. doi: 10.1016/j.proeng.2016.07.325
8. Liu, R. Treatment of low-turbidity source water by permanganate pre-oxidation: In situ formed hydrous manganese dioxide as filter aid [Text] / R. Liu, L. Sun, R. Ju, H. Liu, J. Gu, G. Li // Separation and Purification Technology. – 2013. – Vol. 117. – P. 69–74. doi: 10.1016/j.seppur.2013.04.007
9. Kim, K.-Y. A hybrid microfiltration–granular activated carbon system for water purification and wastewater reclamation/reuse [Text] / K.-Y. Kim, H.-S. Kim, J. Kim, J.-W. Nam, J.-M. Kim, S. Son // Desalination. – 2009. – Vol. 243, Issue 1-3. – P. 132–144. doi: 10.1016/j.desal.2008.04.020
10. Orlov, V. Simulation the process of iron removal the underground water by polystyrene foam filters [Text] / V. Orlov, A. Safonyk, S. Martynov, S. Kunytskyi // International Journal of Pure and Apllied Mathematics. – 2016. – Vol. 109, Issue 4. doi: 10.12732/ijpam.v109i4.11
11. Mwakabona, H. T. Metallic iron for safe drinking water provision: Considering a lost knowledge [Text] / H. T. Mwakabona, A. I. Ndé-Tchoupé, K. N. Njau, C. Noubactep, K. D. Wydra // Water Research. – 2017. – Vol. 117. – P. 127–142. doi: 10.1016/j.watres.2017.03.001
12. Schöntag, J. M. Water quality produced by polystyrene granules as a media filter on rapid filters [Text] / J. M. Schöntag, B. S. Pizzolatti, V. H. Jangada, F. H. de Souza, M. L. Sens // Journal of Water Process Engineering. – 2015. – Vol. 5. – P. 118–126. doi: 10.1016/j.jwpe.2015.02.001
13. Pérez-Vidal, A. Long-term evaluation of the performance of four point-of-use water filters [Text] / A. Pérez-Vidal, J. Diaz-Gómez, J. Castellanos-Rozo, O. L. Usaquen-Perilla // Water Research. – 2016. – Vol. 98. – P. 176–182. doi: 10.1016/j.watres.2016.04.016
14. Hrabovskyi, P. O. Chyselna realizatsiya matematychnoi modeli filtruvannia [Text] / P. O. Hrabovskyi, N. O. Hurinchyk // Problemy vodopostachannia, vodovidvedennia ta hidravliky. – 2005. – Issue 6. – P. 4–13.
15. Polyakov, V. L. Osvetlenie suspenzii fil'trovaniem s ubyvayushchim raskhodom [Text] / V. L. Polyakov // Dopovid natsionalnoi akademii nauk Ukrainy. – 2010. – Issue 5. – P. 57–63.
16. Qin, Z. A statistical model of pressure drop increase with deposition in granular filters [Text] / Z. Qin, R. H. Pletcher // Advanced Powder Technology. – 2015. – Vol. 26, Issue 1. – P. 49–55. doi: 10.1016/j.apt.2014.08.003
17. Minc, D. M. Teoreticheskie osnovy tekhnologii ochistki vody [Text] / M. D. Minc. – Moscow: Stroyizdat, 1964. – 155 p.

18. Ivanchuk, N. Mathematical modeling and computer simulation of the filtration processes in earth dams [Text] / N. Ivanchuk, P. Martynyuk, T. Tsvetkova, O. Michuta // Eastern-European Journal of Enterprise Technologies. – 2017. – Vol. 2, Issue 6 (86). – P. 63–69. doi: 10.15587/1729-4061.2017.98712
19. Martynov, S. Yu. Modeliuvannia roboty pinopolistyrolnykh filtriv zi zminnoiu shvydkistiu filtruvannia [Text] / S. Yu. Martynov // Visnyk NUVHP. – 2014. – Issue 2 (66). – P. 262–269.
20. Polyakov, V. L. Fil'trovanie suspenzii s peremennym soderzhaniem vzvesi cherez odnorodnuyu zagruzku pri nelineynoy kinetike massoobmena [Text] / V. L. Polyakov // Dopovid natsionalnoi akademyi nauk Ukrainy. – 2009. – Issue 12. – P. 61–68.
21. Orlov, V. Water defferization in polystyrene foam filters with sediment layer [Text] / V. Orlov, S. Martynov, S. Kunitsky. – Saarbrucken, Deutschland: LAP LAMBERT Academic Publishing, 2016. – 94 p.
22. Lin, T. Particle properties in granular activated carbon filter during drinking water treatment [Text] / T. Lin, W. Chen, L. Wang // Journal of Environmental Sciences. – 2010. – Vol. 22, Issue 5. – P. 681–688. doi: 10.1016/s1001-0742(09)60163-7
23. Orlov, V. O. Vodoochysni filtry iz zernystoiu zasypkoiu [Text] / V. O. Orlov. – Rivne: NUVHP, 2005. – 163 p.
24. Orlov, V. O. Proektuvannia stantsyi proiasnennia ta znebarvlennia vody [Text] / V. O. Orlov, S. Yu. Martynov, A. M. Orlova. – Moscow: Stroyizdat, 1995. – 176 p.
25. Hirol, M. M. Doslidzhennia roboty filtra iz pinopolistyrolnym filtruiuchym sharom ta aeratsiynoiu kameroiu i obgruntuvannia yoho parametriv roboty [Text] / M. M. Hirol, Yu. P. Trach // Visnyk NUVHP. – 2014. – Issue 1 (65). – P. 137–145.
26. DSTU 7525:2014. Voda pytna. Vymohy ta metody kontroliuvannia yakosti zatverdzhenyi Nakazom Minekonomrozvytku Ukrainy vid 23.10.2014 No. 1257 [Text]. – Kyiv, 2014.

UDC 697.244+621.3.082.1
DOI: 10.15587/1729-4061.2017.111846

THERMAL TREATMENT OF CONCENTRATED LIQUID TOXIC WASTE AND AUTOMATIC CONTROL OF PROCESS EFFICIENCY

V. Nikolsky
Doctor of Technical Sciences, Professor
Department of Energetic**
E-mail: vnikols1@gmail.com
O. Oliynyk
PhD, Associate Professor*
E-mail: oleinik_o@ukr.net
A. Shvachka
PhD, Associate Professor*
E-mail: AleksandrShvachka@gmail.com
I. Nachovny
PhD, Associate Professor
Department of Mechanical Engineering and Engineering Mechanics**
E-mail: mech@udhtu.edu.ua
*Department of Computer-integrated Technologies and Metrology**
**Ukrainian State University of Chemical Technology
Gagarina ave., 8, Dnipro, Ukraine, 49005

Розроблена енерготехнологічна система і спосіб термічної переробки рідких токсичних відходів на основі глибокого термічного упарювання в апаратах заглибного горіння. Встановлено, що щільність і в'язкість РТВ можна використовувати для оцінки ефективності процесу термічного упарювання. Розроблено метод контролю щільності і в'язкості РТВ, що упарюються вібраційним методом з використанням занурювального механічного резонатора. Наведено блок схему розрахунку щільності і в'язкості при багатоконтурному контролі параметрів

Ключові слова: рідкі токсичні відходи, термічне упарювання, аппарат зануреного горіння, вібраційний метод контролю, механический резонатор

Разработана энерготехнологическая система и способ термической переработки жидких токсичных отходов на основе глубокого термического упаривания в аппаратах погружного горения. Установлено, что плотность и вязкость ЖТО можно использовать для оценки эффективности процесса термического упаривания. Разработан метод контроля плотности и вязкости упариваемых ЖТО вибрационным методом с использованием погружного механического резонатора. Приведена блок схема расчета плотности и вязкости при многоконтурном контроле параметров

Ключевые слова: жидкие токсичные отходы, термическое упаривание, аппарат погружного горения, вибрационный метод контроля, механический резонатор

1. Introduction

Liquid toxic waste (LTW) accounts for 30 to 50 % of the total amount of wastewater entering the basins of Ukraine [1]. Development of nuclear power and extension of the scope of radioactive isotopes in various fields of science and technology are associated with pollution of natural waters with radioactive waste. Radioactively contaminated