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REUSED FABRICS IN THREE-LAYER FILTERS: PERFORMANCE AND MODELING

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Abstract - This work investigates the mechanical water purification process, especially by combining a cartridge filter with a textile layer and a granular loading to enhance water filtration from a source area. Based on previous experiment results, a conceptual three-layer filter (textile–granular–cartridge) is proposed to widen the effective cut-off range and distribute fouling across layers. This work aims to develop a mathematical model of the sequential water filtration in the proposed three-stage water purification filter to determine the change in head (pressure) losses and the concentration of suspended solids in water over time and along the thickness (radius) of the filter loading. The scientific novelty lies in integrating secondary textile resources into a structured multilayer design and outlining a physics-based modeling framework with attachment–detachment kinetics and time-evolving porosity area. The practical value of this study is in demonstrating the feasibility of circular-economy principles in water treatment, where textile waste can be reused as a functional material, reducing costs and environmental burden. The findings provide a foundation for the design of adaptive and portable water purification systems that can operate reliably in emergency conditions and contribute to the sustainable development of urban water infrastructure. This approach also enhances the scalability of filtration systems, making them suitable for diverse urban and industrial applications. The model supports predictive maintenance, optimizing filter regeneration cycles for sustained performance.

Keywords: Reused textiles, Three-layer filter, Mathematical model, Water treatment, Circular economy, Filtration efficiency.

1. Introduction

Modern cities are in a state of constant balance between infrastructure development and preservation of ecological balance. One of the most vulnerable elements of this system is water supply, because the quality of drinking water directly determines the population's standard of living, investment attractiveness and social stability [1, 2]. The problem is complicated by the fact that in many urbanized regions, water sources are subjected to significant anthropogenic load: finely dispersed suspended particles, residues of industrial and domestic waste, as well as toxic compounds, which traditional mechanical treatment systems only partially retain, enter the water bodies [3]. This challenge is particularly evident in the treatment of complex suspensions such as coal slims or activated sludge, where advanced dehydration and purification technologies, like those explored in centrifugation processes, are critical for effective water management [4, 5]. This pushes to search for new materials and solutions that can ensure water treatment's reliability while simultaneously complying with the principles of sustainable development [6, 7]. The integration of reused textiles into filtration systems requires precise manufacturing techniques to ensure consistent material properties, as highlighted by research on technological assurance of machining accuracy for complex components [8]. Such precision is critical for achieving reliable filtration performance in multilayer systems, where material uniformity directly impacts efficiency.

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In this direction, technologies for the reuse of resources attract particular attention, as they solve two problems at once: reducing waste and creating more efficient water purification systems. Textile materials, which were traditionally considered by-products of production, are now considered a potential filter element due to their fibrous structure. Their application in filtration systems aligns with findings from studies on centrifugation, where efficient separation of fine particles enhances overall system performance [4]. Their integration into multilayer purification systems, in combination with cartridge filters, can become an effective tool for overcoming the problem of rapid wear and clogging of standard filter elements.

2. Analysis of Literature Data and Problem Statement

A literature review of materials and technologies used for mechanical water purification showed that natural fibrous materials, such as cotton or palm fiber [9], have environmental appeal and availability. However, their disadvantages include limited durability and instability of filtration properties. The use of textile waste or agricultural residues in filtration systems allows not only to reduce the cost of the process, but also to reduce the burden on the environment [10], which is entirely consistent with the concept of a circular economy. Similarly, research on the dehydration of activated sludge highlights the potential of combining mechanical separation techniques with sustainable material use to optimize resource recovery and minimize waste [5]. Modern nanomaterials, for example, graphene oxide [11, 12] or chitosan [13], demonstrate high sorption properties, but their production requires significant resources. Ceramic materials based on fiberglass waste exhibit high porosity and efficiency in retaining suspended solids [14], but their use at high hydraulic loads is limited.

Our laboratory studies [1] have shown the potential of combining cartridge elements with additional layers of textile materials. The experiments demonstrated that cotton and satin fabrics can capture particles of various sizes from several micrometers up to several tens of micrometers, thereby enhancing the overall filtration efficiency by approximately 15–20%. These findings are consistent with studies on centrifugation systems, which demonstrate improved particle retention through optimized mechanical processes [4]. Such findings highlight the potential of secondary textile use, as these materials typically end up as waste and contribute to environmental burden [15].

We have proposed a design for a three-stage water purification filter (Fig. 1), consisting of the metal cartridge filter element wrapped in filter fabric and supplemented with granular filter material (sand or anthracite). Water containing suspended solids sequentially passes through the textile fabric layer, the granular filter material and the metal cartridge filter.

In this context, an important direction for further research is the development of mathematical modeling of processes occurring in multilayer filtration systems. The proposed filter design, which integrates a metal cartridge element, an additional textile layer, and granular filter loading, requires a comprehensive description of the hydrodynamics of flow through all layers. Mathematical modeling of such systems can draw inspiration from centrifugation studies, where precise modeling of particle separation and flow dynamics has been shown to optimize system performance [4, 5]. A mathematical model should enable a quantitative assessment of how filtration resistance evolves, while also considering particle deposition on fibers and grains, their aggregation, and pore clogging mechanisms. Such modeling will make it possible to predict the optimal duration of the filtration cycle, justify the structural and operational parameters, and determine the critical concentrations of suspended solids at which system efficiency decreases sharply.

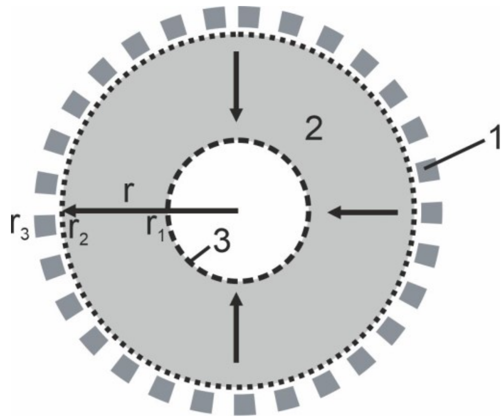

Figure 1: Schematic representation of the three-stage filter element: 1 – textile layer; 2 – granular filter loading layer; 3 – metal cartridge filter

The aim of this study is to develop a mathematical model of the sequential water filtration and purification process in the proposed filter.

3. Research Methodology

The task of mathematical modeling is to determine the change in head (pressure) losses and the concentration of suspended solids in water over time and along the thickness (radius) of the filter media [16, 17].

Filtration of low-concentration suspensions through different types of filter loading can occur:

1. The first type of filtration is forming of a sludge layer on the surface of the porous partition.

2. The second type of filtration is the gradual clogging of the filter media pores.

3. The third type of filtration is the complete blockage of an individual pore of the partition by a single suspended particle.

For granular loading, depending on the grain size, the following filtration modes may be observed:

- The first type of filtration occurs when the medium consists of fine grains.
- The second type of filtration occurs when the medium consists of medium- or coarse-sized grains.

For porous partitions, represented either by a textile layer made of fabric materials or by a metallic catridge filter, all three types of filtration can occur.

To develop a mathematical model of the water filtration process through a multilayer filter, the following assumptions and simplifications were adopted:

1. Liquid flow through the granular loading and porous partitions occurs under laminar conditions.

2. The contribution of the diffusive component to the transfer suspended particles during filtration through the granular loading and the textile layer is negligible compared to other mechanisms (convection and the transfer of suspended particles from the liquid phase to the solid surface).

3. The kinetics of changes in suspended solids concentration within the considered porous loading are assumed to be linear.

4. The thickness of the porous partitions and the sludge layers formed on them is small compared to the radius of the filtering element; therefore, variations in the filtration area across their thickness can be neglected.

The development of such models requires advanced simulation techniques to ensure accurate representation of complex filtration dynamics, as demonstrated in studies on manufacturing process simulations [18]. These simulations are critical for optimizing the design of multilayer filtration systems, particularly when integrating novel materials like reused textiles, to achieve consistent performance under varying operational conditions.

The process of water filtration through the layers of the filter element (Fig. 1) could be described by the equation:

$$\frac{dW(t)}{dt} = \frac{\Delta p(t)}{\mu\left(\frac{R_{\text{layer1}}(t)+R_1(t)}{F_1(t)}+\frac{R_2(t)}{F_2(r)}+\frac{R_{\text{layer3}}(t)+R_3(t)}{F_3(t)}\right)} \tag{1}$$

where t is the time of water filtration;

r is the coordinate that is directed from the outside of the filter element to the center;

$\Delta p(t)$ is the pressure drop (or head loss);

$W(t)$ is the volume of filtered water;

$R_{\text{layer1}}(t)$ is the resistance of the sediment layer on the textile partition;

$R_1(t)$ is the resistance of the textile partition;

$R_2(t)$ is the resistance of the granular loading;

$R_{\text{layer3}}(t)$ is the resistance of sediment layer on the metal mesh of the filter;

$R_3(t)$ is the resistance of the metal mesh layer;

μ is the dynamic viscosity coefficient;

$F_1(t)$ is the filtration area of the porous textile partition;

$F_2(r)$ is the filtration area of the granular loading;

$F_3(t)$ is the filtration area of the porous metallic mesh partition.

The filtering element can operate under a constant pressure drop Δp, or as part of a system with other equipment, such as a pump. In this case, the following dependence can express the general correlation between the pressure drop and the filter capacity:

$$\Delta p(t) = p_0 - \zeta Q(t)^2 \tag{2}$$

where p_0 and ζ are coefficients determined as a result of hydraulic calculations.

The resistance of porous partitions and granular loading under gradual pore clogging can be determined by:

$$R(t) = \int_{r_{i+1}}^{r_i} \rho(r,t)dz \tag{3}$$

where $\rho(r,t)$ is specific resistance of the filter loading (granular loading or porous partitions);

$r_i - r_{i+1}$ is the thickness of the filter loading.

Clogging of the filter loading affects its porosity and, consequently, its specific resistance. The variation of porosity $n(r, t)$ and specific resistance resulting from colmatation can be accounted for using the following equations:

$$n(r,t) = n_0 - \frac{S(r,t)}{\gamma} \tag{4}$$

$$\rho(r,t) = \rho_0 \left(\frac{n_0}{n(r,t)}\right)^3 \tag{5}$$

where n_0 is the porosity of the filter loading at the beginning of the filtration cycle;

ρ_0 is the resistance of the filter loading at the beginning of the filtration cycle;

γ is the concentration of suspended solids in the sludge;

$S(r,t)$ is concentration of impurities retained in the pores of the filter loading.

The parameter S(r, t) is calculated using the following equations:

- mass transfer (kinetics) of suspended particles from water into the solid phase of the filter loading:

$$\frac{\partial S(r,t)}{\partial t} = b(r,t)C(r,t) - a(r,t)S(r,t) \quad (6)$$

- the equation of suspended particle transport by the fluid flow:

$$n(r,t)\frac{\partial C(r,t)}{\partial t} + \frac{\partial\left(V(r,t)C(r,t)\right)}{\partial z} + \frac{\partial S(r,t)}{\partial t} = 0 \quad (7)$$

where C(r,t) is the concentration of suspended particles in the filtrating liquid;
V(r,t) is the filtration rate;
a (r,t) and b(r,t) are the coefficients of detachment and attachment of suspended particles to the filter media, respectively.

To solve the equation (7), the corresponding boundary condition should be specified, namely, at the boundary $r = r_2$, the concentration of suspended solids $C(r_2, t)$ is taken into consideration of the pre-treatment on the porous partition made of textile materials.

Then, the filtration velocity, taking into account the variation of the filtration area along the radius r, is equal to:

$$V(r,t) = \frac{1}{F(r,t)}\frac{dW(t)}{dt} \quad (8)$$

where F(r,t) is the filtration area at point r at time t.

The coefficients a(r, t) and b(r, t) can be calculated using the equations proposed by D.M. Mintz [19] for granular loading:

$$a(r,t) = \frac{V(r,t)}{d}\alpha;\ b(r,t) = \beta\frac{\left(V(r,t)\right)^{0,7}}{d^{1,7}} \quad (9)$$

where α and β are the coefficients that account for the physicochemical properties of the filter grains and the suspension being filtered through them;
d is the grain size of the granular filter loading or pore size of the porous partitions.

The coefficients α and β are determined by identifying the mathematical model.

If the filtration process in a porous partition is studied, the probability of the following processes should be considered. The concentration of sludge in the pores of the partition is significantly higher than in the granular layer. The retained sludge, occupying part of the pore space, not only affects the filtration characteristics of the partition but also influences its retention capacity due to pore size reduction; the probability of suspended particle adhesion to the wall of the partition increases (Fig. 2).

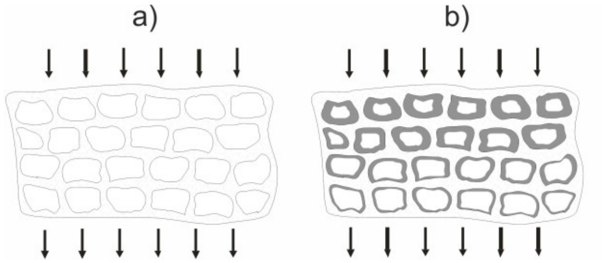

Figure 2: The Structure of the porous partition: a) unclogged b) clogged

The effect of clogging on the retention capacity of the porous partition can be taken into account by adjusting the dependencies (9), which include the pore size d:

$$a(r,t) = \alpha\frac{V}{d}\left(\frac{n_0}{n(r,t)}\right)^{\frac{1}{3}};\ b(r,t) = \beta\frac{V^{0,3}}{d^{1,7}}\left(\frac{n_0}{n(r,t)}\right)^{0,567} \quad (10)$$

In the case of filtration accompanied by the formation of a sludge layer on the surface of the porous partition, the hydraulic resistance of the partitions, whose pores are not subject to clogging under this filtration regime, remains constant and is given by:

$$R_{0.} = r_0(r_i - r_{i+1}) \quad (11)$$

The resistance of the sludge layer is given by

$$R_{slud.layer}(t) = r_{slud.layer} \times h_{slud.layer}(t), \quad (12)$$

where $h_{slud.layer}(t)$ is the thickness of the sludge layer.

The thickness of the sludge layer ($h_{slud.layer}$) is determined by the volume of water that has passed through the filter and by the concentration of suspended particles with sizes greater than the filtration cut-off of the porous partition, d_p:

$$dh_{slud.layer}(t) = \frac{dW(t)}{F}\frac{\left(C_0 - C_f\right)}{\rho_{slud}} \quad (13)$$

$$h_{slud.layer}(t) = \frac{1}{t}\int_0^t dh_{slud.layer}(t)dt \quad (14)$$

where $dh_{slud.layer}$ is the increase in the thickness of the sludge layer;

C_0 is the concentration of suspended solids in the influent to the porous partition;

C_f is the concentration of suspended solids in the effluent after passing through the partition.

When the sludge layer is formed on the surface of the third layer, specifically, the metallic mesh in direct contact with the granular filter loading, the calculation of the sludge layer thickness should include the volume fraction occupied by the granular loading (Fig. 3).

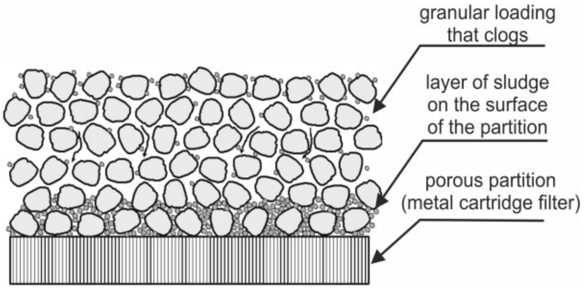

Figure 3: Formation of sludge layer above the porous partition located after the granular loading

$$dh_{slud.layer}(t) = \frac{dW(t)}{F} \frac{\left(C_0 - C_f\right)}{\rho_{slud.layer} n_{0cl.}} \quad (15)$$

where $n_{0\ cl.}$ is the porosity of the non-clogged granular loading.

The specific resistance of the sludge ($\rho_{slud.layer}$) is evaluated from experimental data or, in the case of coarse granular sludge, may be estimated by applying the Kozeny–Carman equation:

$$\rho_{slud.layer} = k_1 F^2_{spec.\,slud.} \frac{(1-n_{slud})^2}{n^3_{slud}} \quad (16)$$

where $F_{spec.\,slud.} = \frac{6F_f}{d_{part}}$ is the specific surface area of sludge particles, for spherical particles F is 1;

n_{slud} is the porosity of the sludge;

k_1 is the ratio of pore length to pore size.

The equation (16) was obtained for granular loading; in the case of porous partition materials, whose characteristic parameter is the equivalent pore diameter, the appropriate equation to be applied is:

$$\rho_0 = \frac{k_1 F^2_{spec.surf.p.p.}}{n_{0\ p.p.}} \quad (17)$$

where $F_{spec.surf.p.p.}$ is the specific surface area of pores in porous partitions.

In the absence of a sludge layer on the porous partitions, the terms $R_{layer1}(t)$ and $R_{layer3}(t)$ in the equation (1) become zero. When liquid straining through porous partitions takes place under the condition that an individual suspended particle completely blocks a pore, the hydraulic resistance remains constant in time. Consequently, the effective filtration surface F(t) decreases as pore blocking progresses. Under alternative filtration regimes, the filtration surface area remains constant over time.

During the pore-blocking process, the free pore area available for water flow decreases with time.

$$F(t) = F_0 - \frac{F_{susp.}(t)}{C_f} \quad (18)$$

where F_0 is the initial value of the partition surface area;

C_f is the ratio of the pore area to the total filtration surface area;

$F_{susp.}(t)$ is the pore area blocked by suspended particles at time t, determined according to the following equation:

$$F_{susp.}(t) = N(t)\frac{\pi d^2_{rate}}{4} \quad (19)$$

where N(t) is the number of suspended particles with diameter $d_{part} \geq d_{rate}$ in the water filtered up to time t;

d_{rate} is the filtration rating of the porous partition.

The number of suspended particles is determined as:

$$N(t) = \int_{d_p}^{\infty} e(d_{part}) \frac{W_{susp.}(t)}{W_1} dd_{part} \quad (20)$$

where $e(d_{part})$ is the probability density function of the size distribution of suspended particles with diameter d_{part};

$W_{susp.}(t)$ is the volume of suspended matter retained on the surface of the porous partition.

W_1 is the volume of a single suspended particle.

Thus, the volume of suspended solids $W_{susp.}(t)$ retained on the surface of the porous partition depends on the amount of water filtered during time t and is determined as:

$$W_{susp.}(t) = \frac{C_0 E(d_{rate})}{\rho_{slud}} W(t) \quad (21)$$

where C_0 is the concentration of suspended solids in the influent water entering the partition ;

$E(d_{rate})$ is the fraction of suspended particles with size $d_{rate} \geq d_{part}$ in the raw water.

4. Results

The presented mathematical model makes it possible to investigate the influence of various factors on the filter's work.

The correlation between the parameters of the filter loading and the size of contaminant particles in the treated water determines the predominant filtration mechanism that can be realized in the proposed filtration device.

Fig. 4 shows the calculation example demonstrating how the filtration regime affects the volume of purified water.

In the case of straining and granular-layer filtration, the turbidity of the raw water plays a decisive role in determining process efficiency. The mathematical model was applied to investigate this effect under various filtration modes, with representative calculation results presented in Fig. 5.

The results of the calculations (Fig. 4, Fig.5) are presented in dimensionless form, representing the ratio of the current value to the maximum value assumed or obtained in the computations.

The numerical findings reveal that the filtration regime significantly influences the volume of treated water and, consequently, the operational efficiency of the device, which in turn governs the required frequency of filter regeneration.

The least rational option is the combination of filter parameters that results in the first type of filtration, where a single suspended particle can completely block a pore of the textile filter. Greater preference should be given to the second and third types of filtration, while the specific choice between them depends on the characteristics of the sludge and the granular filter loading, such as porosity and particle (grain) size. The influence of these key factors is expected to be addressed for future research.

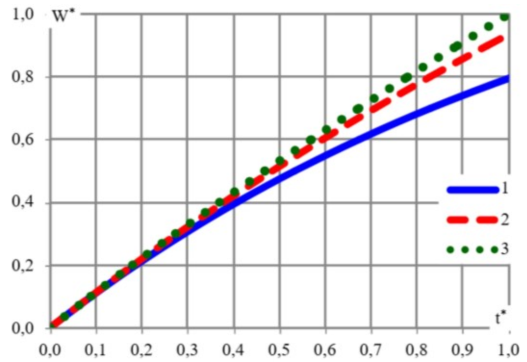

Figure 4: Variation of the volume of purified water over time in the filtration device: 1 – first type of filtration; 2 – second type of filtration; 3 – third type of filtration.

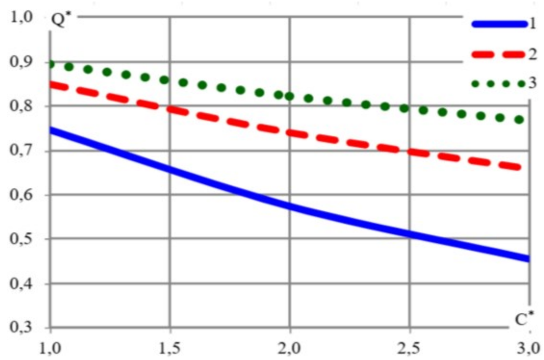

Figure 5: Correlation between the average capacity of the filtration unit and the turbidity of the raw water: 1 – first type of filtration; 2 – second type of filtration; 3 – third type of filtration.

Detailed determination of the particle-size distribution of insoluble impurities in water, along with a well-substantiated selection of filtration's structural and technological parameters, will ensure the required purification quality at minimal operational costs.

5. Conclusions

Thus, the study confirmed the effectiveness of a multilayer filtration system that combines a cartridge element, a textile layer, and granular loading for mechanical water purification. Experimental results demonstrated that reused textiles such as cotton and satin increased fine-particle retention by 15–20%, reduced clogging rates, and extended the service life of the cartridge. The developed mathematical model successfully represented the hydrodynamics of flow through the multilayer structure, capturing particle deposition, pore-blocking mechanisms, and the time-dependent variation of specific resistance. Based on previous research, we have proposed the three-layer filter integrating a textile material, granular media, and a cartridge element, and the obtained results confirmed the feasibility and efficiency of this design. Numerical simulations showed that the filtration regime has a decisive influence on the treated water volume and regeneration frequency, emphasizing the critical role of selecting appropriate media parameters and influent water characteristics. The practical significance of this work lies in integrating circular-economy principles with improved ecological and economic sustainability of water treatment technologies. Future research will focus on pilot-scale testing under real conditions, selection and integration of multilayer filtration with complementary purification methods to ensure safe and sustainable drinking water supply.

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