DEVELOPMENT OF HIGH-EFFICIENCY REPLACEMENT FILTERS FOR PURIFICATION OF DRINKING WATER ON HOUSEHOLD FILTER PITCHERS

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Water filter pitchers s are the simplest and most affordable devices for local purification of drinking water from centralized and decentralized water sources. The main filter element of such pitchers is a cartridge containing a mixture of sorption materials that are able to absorb certain impurities from the water. However, as previous studies demonstrated, the quality of water, purified with filter pitcher cartridges currently available on the market, does not usually reach the level sufficient to meet the standards for drinking water, which are specified in the document DSanPin 2.2.4-171 -10 "Hygienic requirements for drinking water intended for human consumption", while maintaining compliance with consumer needs. Therefore, the aim of this study is to develop a cartridge for filter pitchers, which would provide high efficiency of purification of tap water in Kyiv from the most common impurities: chlorine, organic compounds and hardness ions. In this work, 5 newly created cartridge samples with different ratios of sorption material content, drainage material density, cartridge filling density, presence or absence of inert material in the loading were studied to identify the impact of these factors on water purification efficiency and water filtration rate, as well as the connection between these parameters.

According to the results of the study, a cartridge for a filter pitcher was proposed and determined its the optimal composition. It provides adjustment of tap water composition, namely: reduction by 60 % of the average concentration of chlorine (per 150 dm^3 of water), by 15 % - permanganate oxidizability and by 20 % concentration of hardness ions to standard values at filtration rate not less than 0.15 dm^3/min and a resource of 150 dm^3. These results were achieved by selecting the optimal ratio of the components of the filter loading mixture and the density of the bottom drainage material.

***Key words**: activated carbon, cartridge, chlorine, filter pitcher, water hardness, weak acid cation exchange resin*

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1. Introduction

The quality of drinking water in Ukraine, both from centralized and decentralized water supply sources, is subject to regulation and must meet all the requirements specified in the document DSanPin 2.2.4-171-10 "Hygienic requirements for drinking water intended for human consumption" (DsanPin 2.2.4-171-10, 2010). However, when monitoring water quality, certain samples often exceed the values of certain parameters (oxidation, chromaticity, turbidity, total hardness, content of iron, manganese, chlorine, etc.). Such water samples are called non-standard. Unfortunately, the number of these samples in water from various sources in Ukraine is growing year by year and in 2019 reached 5% for sanitary-bacteriological and 15% for sanitary-chemical indicators in municipal water mains, and 10% and 25%, respectively in water from rural and departmental water mains (National report, 2020).

Literary review

The most common impurities present in non-standard samples of water from centralized water sources are organic substances of natural origin (humic compounds, which are always present in surface waters and especially in the Dnipro and rivers of its basin), that increase the colour and oxidation of water; hardness ions; as well as chlorine and its organic compounds that enter drinking water during its preparation at centralized water treatment plants (Mitchenko et al., 2020). These impurities significantly impair the physicochemical and organoleptic properties of drinking water. Tap water, which has previously been treated at centralized water treatment and consumer facilities, often contains such substances in quantities that do not meet the requirements of DSanPin (DsanPin 2.2.4-171-10, 2010). This leads to the conclusion that water from centralized water sources is not actually drinkable and with regular consumption can be dangerous to human health (Mitchenko, 2019).

Therefore, in order to obtain reliably clean and safe drinking water, the best option is to use local Point-of-use (POU) water treatment systems. Among such systems, filter pitchers are very popular due to their availability, affordability and ease of use. There is a large number of such devices on the market provided by different manufacturers. However, as the results of our previous research demonstrated, the vast majority of them are not able to bring water quality to regulatory levels while maintaining compliance with consumer needs, and advertising information provided by manufacturers is not always true (Bolshak et al., 2020).

The most affordable system for domestic drinking water treatment is a filter pitcher. This device allows you to remove major impurities from the tap water and get clean and safe drinking water (Maletsky, 2012).

Filter pitchers are portable household filters of sorption type, which, unlike a flow filter, do not require connection to the water mains. The design of such filters usually includes the following structural elements:

- main tank - jug;
- a funnel into which water is poured;
- cartridge - the main filter element (Bolshak et al., 2020).

The filter pitcher works according to the following principle: the source water is poured into the upper part of the filter - a funnel into which a replaceable cartridge with a filter loading is inserted. The water flows through the layer of filter components of the cartridge, where it is treated from impurities. Purified water flows out of the cartridge and collects in the lower part of the filter - the jug (Martino, 2022).

The dimensions of the cartridges for the filter pitcher are minimal - the volume of filter loading varies between 90-250 cm^3.

Preferably the cartridges are filled with a mixture of coconut shell activated carbon and weak acid cation exchange resin in a ratio of 1-1.5: 1-1.3. In some cases, the mixture includes fibrous material with special properties (Humbert et al., 2008).

As top and bottom drain to prevent the removal of filter material, all cartridges contain polypropylene mesh or non-woven materials, such as interlining, polyester fabric, rarely foam or other materials. Various cartridge manufacturers have compositions of the components of the filtering mixture, that at first glance, differ little from each other. However, the use of special additives, as well as changing the ratio of components in the mixture, allows you to create compositions focused on solving certain problems (Nabil et al., 2019; Xu et al., 2020).

In previous studies, the composition and filter loading features of filter pitcher cartridges made by different manufacturers presented on the Ukrainian market were analysed (Bolshak et al., 2020). It should be noted that the information provided by manufacturers of industrial cartridges on the effectiveness of water purification from impurities is not true, and in fact is exaggerated (Bolshak et al., 2020; Trimmer, 2018).

Within the frames of the present work it was planned to create a cartridge for filter pitchers capable of purifying tap water to the level sufficient to meet the requirements enlisted in DSanPin 2.2.4-171-10 "Hygienic requirements for drinking water intended for human consumption" (DsanPin 2.2.4-171-10, 2010) by indicators as total chlorine (TC), permanganate oxidation (PO), hardness at water filtration rate not less than 0.15 dm^3/min and filter capacity not less than 150 dm^3.

These indicators were chosen because two of them (TC and PO) significantly affect the organoleptic characteristics of drinking water, and the third one (hardness) is the cause of scale formation on the surfaces of the reservoirs when boiling water, which causes a negative reaction by filter users. All manufacturers of cartridges for household filter pitchers focus on the efficiency of removing these impurities from the water (Guidelines for drinking-water quality, 1996; Pei et al., 2014).

According to the analysis of the demand for filter pitchers, the claims of buyers also relate to the water filtration rate and its service life. According to users' opinions, the collection time of one litre of purified water should not exceed 5-7 minutes, and the cartridge should be replaced more than once a month (Flamer, 2021). These requirements can be met at a water filtration rate between 100-150 cm^3/min and the service life of the cartridge - 150 dm^3.

Table 1 presents the average data on the composition of tap water in Kyiv for 10 years at the point of consumption in comparison to the requirements of DSanPin2.2.4-171-10 "Hygienic requirements for drinking water intended for human consumption" by quality indicators that interest us (Water quality map, 2021).

According to the data given in Table 1, it can be concluded that the content of hardness ions in the tap water in Kyiv meets the requirements of DSanPin (DsanPin 2.2.4-171-10, 2010) and it is safe for drinking. According to this indicator, water requires adjustment only to prevent scale formation on the surfaces of kitchen utensils when it is boiled during cooking food and drinks.

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Table 1. *Average composition of tap water in Kyiv at the point of consumption in the period from 2010 to 2020, and requirements for drinking water according to DSanPin 2.2.4-171-10 "Hygienic requirements for drinking water intended for human consumption"*

Indicator	**Value**	
	In the tap water of Kyiv, for the period of 2010-2020	**Requirements according to DSanPin**
pH	7.2–7.7	6.5–8.5
Hardness, meq/dm^3	2.7–4.7	< 7.0
Total chlorine, mg/dm^3	0.35–0.45	< 0.5
PO, mgO_2/dm^3	4.2–5.6	< 5.0

At the same time, in order to comply with the requirements of DSanPin (DsanPin 2.2.4-171-10, 2010) in terms of PO indicator, it must be reduced by at least 15%. As for chlorine, its content in tap water in Kyiv, as a rule, meets the requirements of DSanPin (DsanPin 2.2.4-171-10, 2010). However, according to the recommendations of the World Health Organization, the concentration of residual chlorine in the range of 0.2-0.5 mg/dm^3 is optimal for municipal water supply systems. At this concentration of chlorine, water is considered to be acceptable for human consumption. Therefore, according to these requirements, as well as to further improve the organoleptic properties of drinking water from centralized water sources, the filter cartridge must remove chlorine from the water by at least 50 % throughout the service life of the filter (World Health Organization, 2011). According to the results of our previous research, none of the cartridges presented on the Ukrainian market meets such requirements (Bolshak et al., 2020).

The purpose and objectives of the study

The purpose of this study is to create cartridges for filter pitchers that will ensure stable efficiency of tap water treatment from impurities at the level of not less than: 60 % of chlorine; 15 % of PO; 20 % of hardness at a filtration rate of not less than 0.15 dm^3/min and a capacity of 150 dm^3.

To achieve this goal the following tasks have to be done:

1. Study the influence of quality and quantity of components included in the cartridge on the efficiency of water purification from chlorine, PO and hardness.

2. Determine the optimal composition of the cartridge loading for the effective removal of major impurities from the tap water while maintaining the optimal filtration rate.

2. Materials and methods

The main element of the filter pitcher is a cartridge, because it provides purification of water from impurities (Figure 1).

Fig. 1. *The appearance of the experimental cartridge for the filter pitcher in section*

In a previous study, we determined the composition of cartridges by different manufacturers on the Ukrainian market, and found that in all cases it includes activated coconut shell carbon and weak acid cation exchange resin, and the main factor influencing the efficiency of water purification on cartridges is the contact time of water with the filter loading, which is determined by the filtration rate and the volume of loading in the cartridge (Bolshak et al., 2020).

The filtration rate, in turn, depends on the resistance of the cartridge loading filter bed, which is affected by the following factors:

• Particle size distribution of active components of loading;

• Ratio of loading components;

• Availability of aggregates in the loading;

• Density of drainage material;

• Cartridge loading density.

(Made-in-China 2022).

During the experiment, 5 samples of cartridges for filter pitchers with varied loading composition and density of drainage material were studied. The cartridge loading density was 85 %. The composition of the cartridge loading is presented in table 2.

Technical characteristics of weak acid cation exchange resin and coconut shell activated carbon are presented in tables 3 and 4. The inert material was added to the filter mixture to adjust the filtration rate of water through the cartridge (Bolshak et al., 2020).

The cartridges were examined for the efficiency of water purification from chlorine, hardness and PO depending on their filtration rate. Also, during the experiment, the values of pH and alkalinity of the source and filtered water were measured.

The experiment method was to pour Kyiv tap water through a filter pitcher with water sampling for analysis every 10 dm^3 or with a frequency of 10, 50, 100, 150 dm^3. Simultaneously, the source water samples were taken for analysis.

Table 2. *Composition and loading characteristics of experimental cartridges*

Loading component	**1**	**2**	**3**	**4**	**5**
Weak acid cation exchange resin (WAC), %	45	45	58	53	58
Coconut shell activated carbon (AC), %	55	55	42	47	42
Inert material, g	0.85	0.85	-	0.85	0.85
Density of the bottom drainage (non-woven material), g/m^2	200	100	100	100	100

Table 3. *Technical characteristics of coconut shell activated carbon*

Product characteristics	**Parameter value**
Effective size of granules, mesh	30x60
Iodine number (ASTM), mg/g	1039
Bulk density, g/dm^3	476
Mass fraction of water, %	1.0
Mass fraction of ash, %	2.2
pH of water extract	10.4

Table 4. *Technical characteristics of weak acid cation exchange resin*

Characteristics of the commodity form of ion exchange resin	
pH of the filtrate	5.97
Chromaticity of the filtrate, deg.	7.5
Oxidation of the filtrate, mgO_2/dm^3	0.6
Odour of filtrate, points	2
Physicochemical characteristics of the prepared ion exchanger	
Particle size, mm	0.315-1.0
Whole beads count, %	99
Effective particle size, mm	0.47
Uniformity coefficient	1.62
Moisture holding capacity, %	57.85
Specific volume, cm^3/g	3.02
Static exchange capacity, meq/cm^3	4.36
Oxidation of the filtrate, mg/g	0.02
Osmotic stability, %	100

Since the chlorine concentration in the source tap water was low and unstable during the experiment, there was created a model water with a chlorine concentration of 0.5 mg/dm^3. The model water was prepared in an installation consisting of 2 tanks 50 dm^3 each, that were filled with tap water. At the bottom of each tank there is a tap for water extraction. The tanks were tightly closed with a lid after dosing chlorine into the water. The concentration of chlorine in the water was checked 5 times a day and adjusted. The constant concentration of active chlorine in the source water was maintained at 0.5 mg/dm^3 by dosing in tanks additional sodium hypochlorite and mixing of water.

The efficiency of water purification from contaminants (α) was determined by the formula:

$$\alpha = \frac{C_s - C}{C_s} \cdot 100\%,$$

where C_s – the concentration of the contaminant in the source water, mg/dm^3; C – the concentration of the contaminant after filtration on the cartridge, mg/dm^3.

Average values of water purification efficiency (α_{av}, %) for 150 dm^3 were determined by the formula:

$$\alpha_{av} = \frac{\sum_{i=10\ldots150}^{n=10\ldots150} \alpha_i \cdot (V_{i+n} - V_i)}{150},$$

where α_i – efficiency of water purification from the pollutant on the i-th dm^3, %; V_i – volume of i dm^3 of passed water.

The average values of filtration rate and contact time of water with the loading were determined by analogy.

3. Results and discussion

Figures 2-5 present the studying results of the various factors influence on the filtration rate and averaged over the filter cartridge capacity (150 dm^3) values of water treatment efficiency.

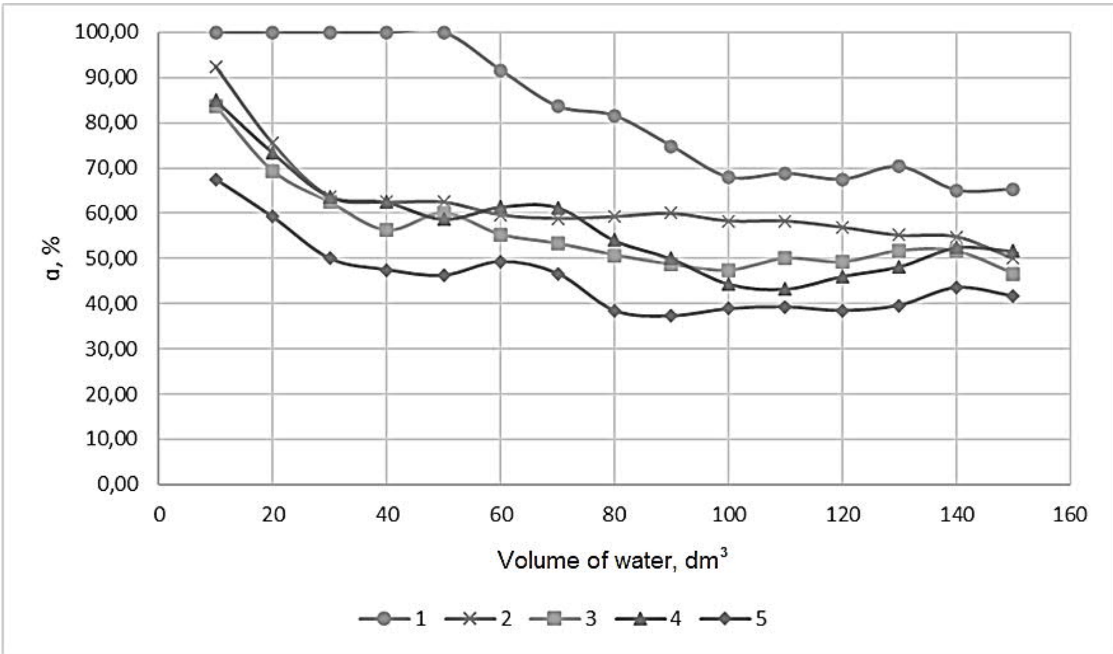

Fig. 2. *The efficiency of water purification from chlorine while filtering 1-150 dm^3 of water on the 1-5 cartridges*

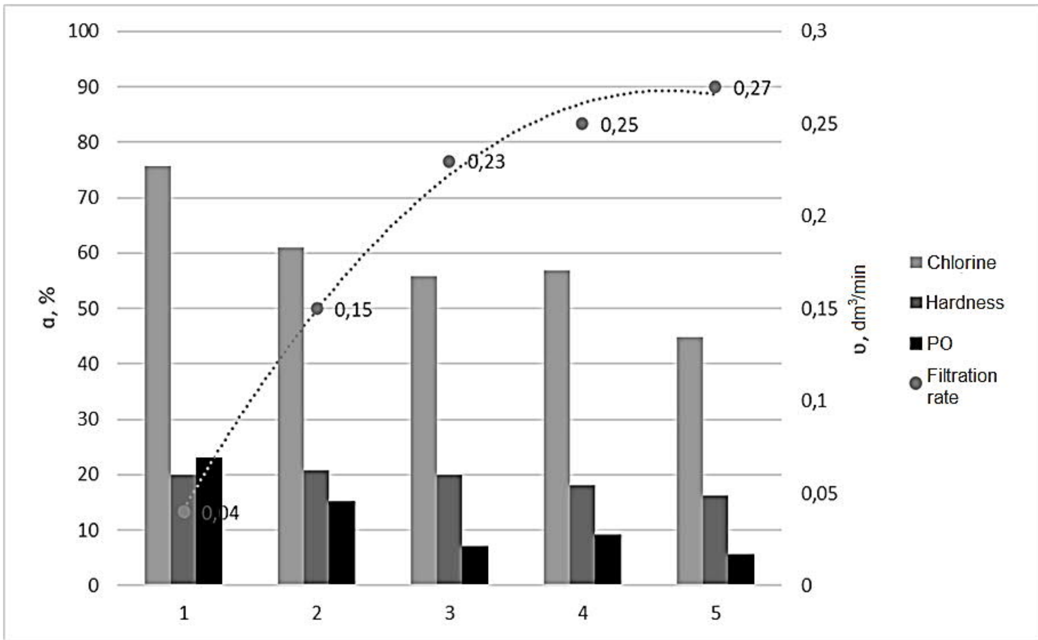

Fig. 3. *The average efficiency of water purification from chlorine, hardness and PO (a, %) and filtration rate (υ, dm^3/min) on 1-5 cartridges*

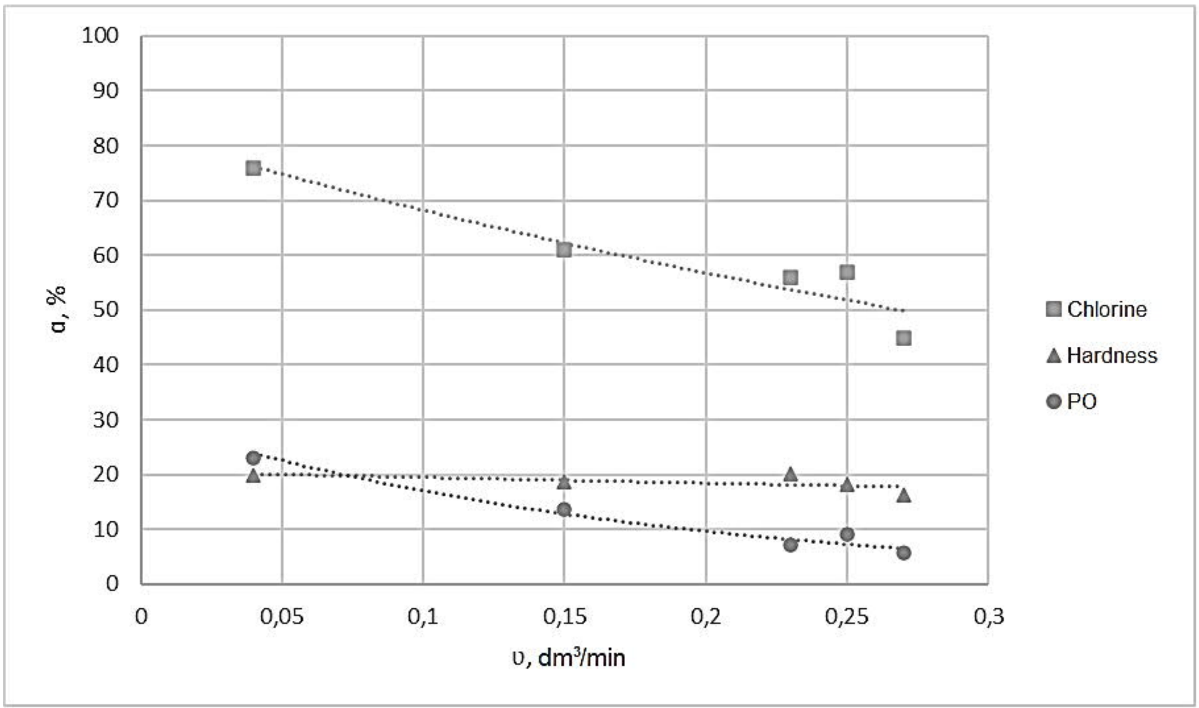

Fig. 4. *The dependence of the average efficiency of water purification (a,%) on the filtration rate (υ, dm^3/min) on 1-5 cartridges*

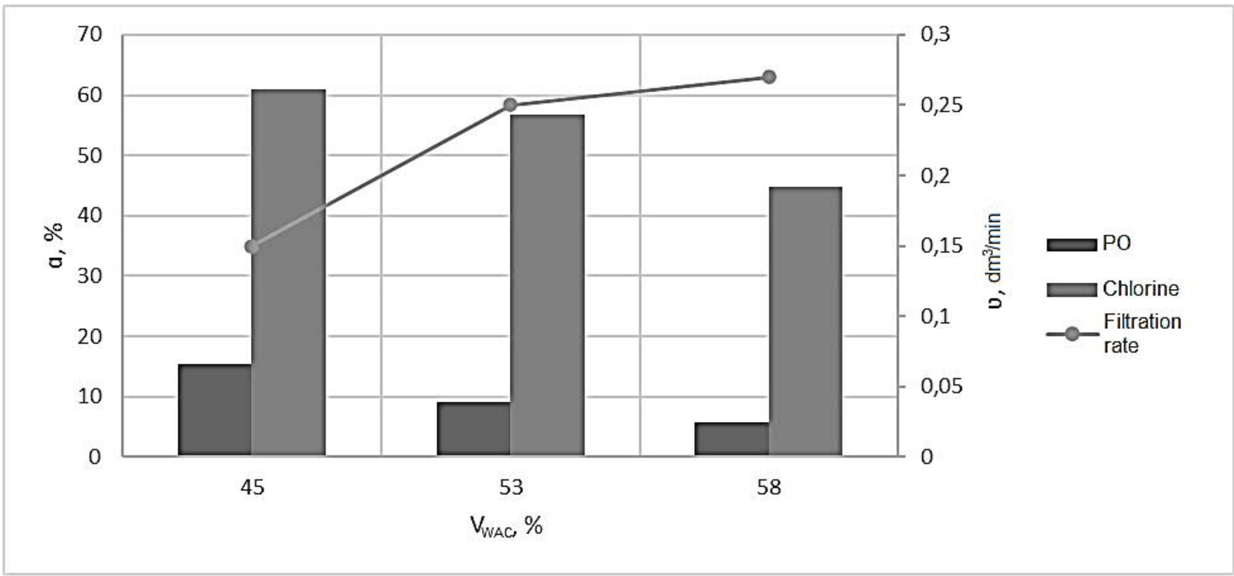

Fig. 5. *Influence of the share of WAC (VWAC,%) in the cartridge loading on the filtration rate (υ, dm^3/min) and treatment efficiency from PO and chlorine (a,%). The density of the bottom drainage is 100 mg/m^2, the amount of inert material is 0.85 g*

The following conclusions can be drawn from Table 2 and Figures 2-5:

1. The volume of WAC increase of components ratio in the loading and reducing the amount of AC leads to an increase in the filtration rate of water on the cartridges from 0.15 dm^3/min at a ratio of WAC:AC - 45:55 % to 0.27 dm^3/min at a ratio of WAC:AC - 58:42 %. This pattern is observed for cartridges, in the loading of which was used inert material weighing 0.85 g and bottom drainage material with a density of 100 g/m^2. In this case, in the absence of inert material in the loading (cartridge 3), the

filtration rate on the cartridge is reduced, but not significantly - from 0.27 to 0.23 dm^3/min at a ratio of WAC:AC - 58:42%.

2. With the increase of the filtration rate on the cartridges, decreases the efficiency of water purification from:

• chlorine - from 61 % (at a filtration rate of 0.15 dm^3/min) to 44.8 % (at a filtration rate of 0.27 dm^3/min);

• hardness ions - from 20.6 % (at a filtration rate of 0.15 dm^3/min) to 16.3 % (at a filtration rate of 0.27 dm^3/min);

• PO - from 15.7 % (at a filtration rate of 0.15 dm^3/min) to 5.7 % (at a filtration rate of 0.27 dm^3/min).

This is due to the fact that with increasing of the filtration rate, the contact time of water with the filter loading decreases, and therefore the efficiency of water purification from impurities also decreases.

3. To study the effect of drainage material density on the efficiency of water purification from impurities and filtration rate, cartridges 1 and 2 were compared. These cartridges have identical loading composition, but different density of drainage material: cartridge 2 - 100 g/m^2, cartridge 1 - 200 g/m^2.

It can be argued that increasing the density of the drainage material significantly increases the efficiency of water purification from chlorine - from 61.06 % (at a density of 100 g/m^2) to 75.82% (at a density of 200 g/m^2); as well as from PO - from 15.72 % (at a density of 100 g/m^2) to 23.14 % (at a density of 200 g/m^2).

The improvement of chlorine purification is especially noticeable when filtering the first 60 dm^3 of water, where the efficiency of water purification on the cartridge with a bottom drainage density of 200 g/m^2, was stable at 100 % during this period. The change in the efficiency of water purification from chlorine during the filtration of 1-150 dm^3 of water on different cartridges is presented in Figure 2.

This happens because with the increasing of density of the bottom drainage material, the filtration rate reduces significantly: from 0.15 dm^3/min (at a density of 100 g/m^2) to 0.04 dm^3/min (at a density of 200 g/m^2). Such a low filtration rate does not meet the purpose of the study.

4. Figure 4 demonstrates how the filtration rate affects the efficiency of water purification from each of the impurities. The figure shows that the most significant increase in filtration rate affects the efficiency of water purification from chlorine, with almost no effect on the efficiency of purification from hardness. Therefore, based on the fact that the removal of hardness from water is carried out exclusively by cation exchange resin, and according to conclusion 1, it can be argued that increasing of the amount of weak acid cation exchange resin in the cartridge does not significantly improve the efficiency of purification of water from hardness, but causes a significant increase in the filtration rate and the associated decrease in the efficiency of water purification from chlorine and organic impurities.

5. A cartridge with optimal values of water filtration rate and efficiency of its purification from impurities was selected from the tested samples. By using this cartridge, it is possible to achieve the requirements formulated in the purpose of work: reduction of average (for 150 dm^3 of the filtered water) concentration of impurities at least by: 60% of chlorine; 15% of PO; 20% of hardness at a filtration rate of not less than 0.15 dm^3/min and a capacity of 150 dm^3. The composition and characteristics of the loading

components of the selected cartridge, as well as the efficiency of water purification on it and the filtration rate are shown in tables 5 and 6.

Table 5. *Composition and loading characteristics of the cartridge with optimal properties*

Loading component	Value
The cartridge loading density, %	85
Weak acid cation exchange resin, %	45
Coconut shell activated carbon, %	55
Inert material, g	0.85
Density of the bottom drainage (non-woven material), g/m^2	100

Table 6. *Water purification efficiency and filtration rate on the cartridge with optimal properties*

Purification efficiency	Average (per 150 dm^3 of filtered water)	Maximum
Chlorine, %	61.06	92.50
PO, %	15.72	21.31
Hardness, %	20.59	50.92

4. Conclusions

According to the results of the work, the purpose of the study was achieved – there was created a cartridge with an average water filtration rate that meets the established limits - 0.1 - 0.15 dm^3/min, as well as with the efficiency of water purification from impurities, which meets certain criteria for all indicators. These results were achieved by selecting the optimal ratio of the components of the filter loading mixture and the density of the bottom drainage material.

The efficiency of water purification from the most common impurities contained in drinking water from centralized sources of water treatment of Ukraine: chlorine, hardness and organic impurities (according to the indicator of permanganate oxidation) on the chosen cartridge was experimentally studied.

The average (per 150 dm^3 of filtered water) filtration rate on the cartridge is 0.15 dm^3/min, and the efficiency of water purification from impurities is not less than: 60% of chlorine; 15% of PO; 20% of hardness. At observance of such level of efficiency of removal of impurities, indicators of quality of water correspond to standards.

At the same time, the further improvement of the efficiency of cartridges for pitcher filters is possible by varying of the components and their volumes in the filter loading.

This is necessary to increase the contact time of the water with the filter loading of the cartridge, which will help to improve the efficiency of water purification from impurities without significant reduction of the filtration rate.

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СТВОРЕННЯ ВИСОКОЕФЕКТИВНИХ КАРТРИДЖІВ ДЛЯ ДООЧИЩЕННЯ ПИТНОЇ ВОДИ НА ПОБУТОВИХ ФІЛЬТРАХ-ГЛЕЧИКАХ

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Найпростішим та найдоступнішим пристроєм для локального доочищення питної води з централізованих та децентралізованих джерел водопостачання є фільтр-глечик. Основним фільтруючим елементом таких фільтрів є картридж, що містить суміш сорбційних матеріалів, які здатні поглинати ті чи інші домішки з води. Однак, як показали попередні дослідження, ефективність доочищення води на картриджах для фільтрів-глечиків, що представлені на ринку, зазвичай не досягає рівня, за якого якість профільтрованої води відповідала би нормативним показникам для питної води, які вказані в документі ДСанПін 2.2.4-171-10 «Гігієнічні вимоги до води питної, призначеної для споживання людиною», при одночасному витримуванні відповідності споживчим потребам. Тому, мета даного дослідження полягала у розробці картриджа для фільтрів-глечиків, який би забезпечував високу ефективність доочищення водопровідної води м. Київ від найбільш поширених для неї домішок: хлору, органічних домішок, а також іонів твердості. В даній роботі дослідженням підлягали 5 новостворених зразків картриджів з різними співвідношеннями вмісту сорбційних матеріалів, густиною дренажного матеріалу, щільністю заповнення картриджу, наявністю чи відсутністю інертного матеріалу в складі завантаження, з метою виявлення впливу цих факторів на ефективність очищення води від зазначених домішок та швидкість фільтрації води через картридж, а також взаємозв'язок цих параметрів. За результатами дослідження запропоновано картридж та визначено його оптимальний склад для фільтра-глечика, який забезпечує корегування складу водопровідної води, а саме: зниження в очищеній воді на 60 % середньої (за 150 дм^3 пропущеної води) концентрації хлору, на 15 % - перманганатної окиснюваності та на 20% концентрації йонів твердості, що відповідає нормативним показникам при швидкості фільтрації не меншій за 0,15 дм^3/хв і ресурсі 150 дм^3.

Ключові слова: *активоване вугілля, картридж, слабокислотний катіоніт, твердість води, фільтр-глечик, хлор*