© 2024 ІМФ (Інститут металофізики ім. Г. В. Курдюмова НАН України) Надруковано в Україні.

PACS numbers: 61.43.Gt, 68.37.Og, 68.43.Hn, 81.05.Rm, 82.70.Kj, 83.80.Hj

## Behaviour of Dispersed Particles in Water Treatment During Lime Softening and Acid Stabilisation Treatment

P. M. Kuznietsov<sup>1,2</sup>, O. V. Yaroschuk<sup>1,2</sup>, O. O. Biedunkova<sup>1</sup>, and A. M. Pryshchepa<sup>1</sup>

<sup>1</sup>National University of Water and Environmental Engineering, 11, Soborna Str., UA-33028 Rivne, Ukraine <sup>2</sup>SE 'Rivne NPP', 1, Promyslova Str., UA-34400 Varash, Ukraine

Nanotechnology is a section of science and technology regarding the modification and use of particles in the atomic and molecular order. In this aspect, a particle is considered a tiny thing that acts as a single piece with respect to its carriage and specifications. The study of the formation of suspended particles in treated water during liming and corrective treatment with sulfuric acid  $(H_2SO_4)$  and 1-hydroxy ethylidene-1,1diphosphonic (HEDP) is carried out, the change in the components of treated water is shown, the particle-sizes' distribution is determined, and microscopic images of suspended particles in treated water are obtained. The purpose of the study is to determine the processes of formation of chemical composition, changes in size and structure of particles formed during lime softening and corrective antiscale treatment of cooling water, the results of which can be used to optimize water-treatment technology in order to reduce the flow of suspended solids into cooling systems. As shown, in the process of water treatment, the composition of suspended solids changes from mixed to calcium carbonate, particles are enlarged, and their content increases compared to the input water that requires the use of additional treatment methods, in particular, filtering of treated water. Lime softening provides water purification for the main components, which form scale: a decrease in the concentration of bicarbonate and carbonate ions is up to 70%, of calcium ions is up to 60%, compared to the input water, and an increase in their concentration is observed for total suspended solids (TSS). Changes in both the chemical content and the particle-sizes' distribution of suspended solids indicate the formation of new particles, which are crucial in the formation of the TSS content in treated water during lime softening. Taking into account the results of determining the TSS concentration and their particle-sizes' distribution

1039

1040 P. M. KUZNIETSOV, O. V. YAROSCHUK, O. O. BIEDUNKOVA et al.

(PSD), a filter material with pores of 20  $\mu m$  is selected, which allows separating up to 70% of particles and reducing the TSS content during water treatment.

Нанотехнологія є розділом науки та техніки стосовно модифікування та використання частинок в атомному та молекулярному порядку; у цьому аспекті частинка вважається крихітною частинкою, яка діє як єдине ціле щодо свого формування та характеристик. Проведено дослідження утворення нерозчинних частинок в освітленій воді за вапнування та корекційного оброблення сірчаною кислотою (H<sub>2</sub>SO<sub>4</sub>) та 1гідроксиетиліден-1,1-дифосфоном (HEDP); показано зміну компонентного складу обробленої води; визначено ґранулометричний склад та одержано мікроскопічні зображення нерозчинних частинок в обробленій воді. Метою роботи було дослідження технології процесів формування хемічного складу, зміни розмірів і структури частинок, що утворюються під час вапнування та кориґувального протинакипного оброблення охолоджувальної води; результати можуть бути використані для оптимізації технології водопідготовки з метою зменшення надходження завислих речовин у системи охолодження. Показано, що в процесі водопідготовки склад завислих речовин змінюється зі змішаного на карбонатний, частинки укрупнюються і їхній вміст збільшується порівняно з вхідною водою, що потребує застосування додаткових методів оброблення, зокрема фільтрування очищеної води. Пом'якшення вапном забезпечує очищення води від основних компонентів, що утворюють накип, — пониження концентрації бікарбонат- і карбонат-йонів до 70%, йонів Кальцію до 60% порівняно з водою, що вводиться, і спостерігається збільшення їхньої концентрації. Зміни в хемічному та ґранулометричному складах завислих речовин за вапнування свідчать про утворення нових твердих частинок, які є вирішальними у формуванні їхнього загального вмісту в очищеній воді. Враховуючи результати визначення концентрації завислих речовин та розмір їхніх частинок, було обрано фільтрувальний матеріял з порами у 20 µм, що уможливлює відокремити до 70% твердих частинок і зменшити вміст завислих речовин під час водопідготовки.

Key words: particle-sizes' distribution, lime softening, chemical composition, suspended particles.

Ключові слова: ґранулометричний склад, вапнування, хемічний склад, нерозчинні частинки.

(Received 2 October, 2023; in revised form, 24 October, 2023)

# **1. INTRODUCTION**

Nanotechnology represents a revolutionary path for technological development that concerns the management of material at the nanometer scale (one billion times smaller than a meter). Nanotechnology factually means any technology on the nanoscale that has numerous applications in the real world. Nanotechnology literally encompasses the fabrication and application of chemical, physical, and biological systems at scales ranging from individual molecules or atoms to submicron dimensions [1]. A nanoparticle is defined as the smallest unit that can still behave as a whole entity in terms of properties and transport. These particles can be categorized, based on their diameter, into three groups, including coarse particles  $(10\ 000-2500\ \text{nm})$ , fine particles  $(2500-100\ \text{nm})$ , and ultrafine particles or nanoparticles (1-100 nm) [2]. Mineral scaling, which is caused by hardness cations (calcium and magnesium) on the surface of any material that comes into contact with water, often causes serious technical and economic consequences in domestic, municipal and industrial water supply systems [3]. Lime softening is a traditional and inexpensive method of water treatment in industry used to reduce water hardness [4]. During lime softening, chemicals are added in order to exceed the solubility product of CaCO<sub>3</sub> and  $Mg(OH)_2$ .

The widespread use of lime softening is limited, as this process creates an excessive amount of sediment and introduces additional components into the treated water [5]. The formation of the dispersion phase during lime softening occurs by two mechanisms: cluster-cluster aggregation for small flakes (< 50 µm) and limited diffusion aggregation for large flakes (> 50  $\mu$ m) [6]. A study of the sludge produced by lime softening showed that it consists of calcium carbonate, and microscopic images and particle-sizes' distribution (PSD) of the sludge demonstrate the differences in water treatment methods on the properties and PSD of the sludge [7]. The industrial application of lime softening is in clarifiers, and many studies on the kinetics of calcium carbonate precipitation have been conducted to determine the rate of calcium carbonate precipitation, but not many studies on the process in terms of PSD [8], however, it has been found that lime softening increases the concentration of total suspended solids (TSS) [9]. During lime softening, the germinal particles of calcium carbonate, which form TSS in clarifiers, do not settle, but are carried away with the treated water [10]. On the one hand, the removal of hardness cations is ensured; on the other hand, the content of suspended solids increases [11]. The temperature effect on the intensification of the lime softening process and the formation of larger and denser flakes of sediment and changes in their composition has been shown [12].

The TSS content in purified water after lime softening depends on the efficiency and dose of the liming technology and is usually  $50-200 \text{ mg/dm}^3$  [14]. The efficiency of dissolved and solids removal during lime softening depends on the PSD and determines the further water treatment processes [15]. Effective filtration methods should be used to remove suspended solids formed during lime softening in industrial applications in order to use water for water treatment in cooling cycles [16]. The selection of filter materials should take into account the technological characteristics, content and morphology of particles in the treated water [17].

The quality of water treatment in the power industry affects the reliability, efficiency, and safety of operation of power plant systems and components, which is why high requirements are placed on the quality of water at power facilities [18]; increasing the temperature to intensify the deposition during liming for water treatment of cooling systems is not advisable [19].

Studies of PSD during lime softening have mainly focused on the growth and aggregation of calcium carbonate precipitate and crystallization processes [20]. It has been established that the morphology of calcium carbonate precipitate during lime softening changes under different conditions of lime concentration [21], the concentration of magnesium ions of 200 mg/dm<sup>3</sup> slows down the kinetics of lime softening, the shape of precipitated particles changes [22], and the wider the range of particle size distribution, the greater the axial deformation of the precipitate [23]. The analysis of literature sources showed the absence of available data on the effect of corrective antiscaling treatment on the size and chemical composition of TSS formed under the combined effect of 1-hydroxy ethylidene-1,1diphosphonic acid (HEDP) and sulfuric acid. A wide variety of lime softening regimes (lime doses, combinations of flocculation and coagulation) make it necessary to individualize studies for a specific object, and the optimization of lime softening water treatment is mainly carried out by trial and error [24]. The final removal of hardness during lime softening depends on the PSD distribution and determines the further methods of treatment processes [25].

Particle sizes in water treatment processes range from a few nanometres to hundreds of micrometres [26]. There is no doubt that particle size is an important parameter, controlling much of the dynamic behaviour of the particles. The scientific emphasis of nanoscience and technology has now shifted to that of measuring, understanding and ultimately predicting the property changes from bulk to nanodomain [27], so this study characterises the results of experimental research in the field of colloidal dispersed systems in water treatment by liming and stabilisation treatment. In order to interconnect aspects of physical and chemical nanoscience with engineering-oriented fields, such as water treatment processes in nuclear power, it is necessary to understand the links between the formation processes, structural properties and functions of particles [28], with the control of morphology (nanoclusters, nanowires, nanotubes, *etc.*), structure, composition and size, *i.e.*, the features that determine the physical properties of particles [29], so the purpose of our research is to determine the processes of formation of the chemical composition, changes in the size and structure of particles formed during water treatment by liming and corrective antiscale treatment of cooling water. The results of the study can be used to optimize the liming technology in order to reduce the supply of suspended particles and to understand how the fine particles are formed, the mechanisms of formation of their particle size and chemical composition.

### 2. EXPERIMENTAL TECHNIQUE DETAILS

The object of research is the make-up water system of the Rivne NPP circulation system. The water treatment of the cooling water of the Rivne NPP circulation system includes pretreatment of lime softening in clarifiers and corrective antiscale treatment and includes the methods specified in Table 1, the water treatment capacity of Rivne NPP is up to 8000  $m^3/h$ , the schematic representation of the Rivne NPP water treatment is shown in Fig. 1. In the lime softening process, slaked lime  $(Ca(OH)_2)$  is added, and the following processes occur: carbon dioxide dissolved in water is bound, and calcium hardness is eliminated. The saturation ratio in lime softening is defined generically and for calcium carbonate as the driving force for precipitation S, where the ionic activity product Ks is the solubility product  $Ca^{2+}$  and  $CO_3^{2-}$  [25]. The rate and degree of  $CaCO_3$ precipitation depends on a number of factors, including the value of the driving force for precipitation, the type and concentration of liquid particles, in lime softening S is variable with time and in the case of Rivne NPP water treatment is determined by the vanpas dose and pH (Table 1). The formation of the solid phase during liming occurs by the reaction of calcium ions and carbonate ions with the formation of a calcium carbonate precipitate (Fig. 2, a), thick-

Method of water treatment	Reagent	Dose, mg/dm <sup>3</sup>	Parameter
Lime softening	Lime	116.7 - 161.4	pH: 8.8–9.8
Antiscale corrective	sulfuric acid H <sub>2</sub> SO <sub>4</sub>	11.5 - 24.5	pH: 7.4–7.6
	HEDP	0.2 – 0.5	by the variability criterion

**TABLE 1.** Textural characteristics methods of water treatment the circulating cooling water Rivne NPP.



Fig. 1. Schematic representation of the water treatment plan of Rivne NPP.



Fig. 2. The formation of a solid phase during liming in laboratory conditions depending on time (contact time: a=3 min, b=15 min, c=30 min, d=40 min, e=80 min for make-up water, and f=80 min for sludge sediment).

ening of the precipitate (Fig. 2, *b*), precipitation (Fig. 2, *c*, *d*) and separation of the liquid and solid phases (Fig. 2, *e*, *f*). The water after water treatment is filtered using high-speed filters VSMP-2000 with a filter mesh size of 50  $\mu$ m. The input water for water treatment is the water of the Styr River, a fishery reservoir.

The determination of PSD with obtaining dependence curves of their quantity distribution was carried out by laser diffraction using a laser particle counter HIAC/ROYCO 8000A respectively ISO 21501, the TSS content in the waters was determined by the gravimetric method according to KND 211.1.4.039-95 (standard in Ukraine), the chemical composition of TSS was measured according to GKD 34.37.304-2003 (standard in Ukraine), optical images were taken using a microscope with a  $20\times$  objective, samples were filtered using NY41 and NY20 filters with a pore size of 40 µm and 20 µm and water samples were collected according to DSTU ISO 5667-6:2009. The measurement data were analysed in accordance with the results presented in the Rivne NPP report and permission was obtained from Rivne NPP to publish monitoring data in open sources (Rivne NPP Act No. 036-08-A-Zag.B of 02.03.2023).

## **3. EXPERIMENTAL RESULTS AND DISCUSSION**

Changes in the Chemical Composition of Water and Suspended Solids during Water Treatment. Changes in the components of the water chemical composition in the process of water treatment at Rivne NPP are shown in Fig. 3. According to the main indicators of water quality, the incoming water of the Styr River and process water are of calcium bicarbonate type. Liming results in a 35% decrease in the concentration of bicarbonate and carbonate ions, further corrective treatment with  $H_2SO_4 + HEDP$  neutralizes free alkalinity and reduces the content of carbonate ions, and the total decrease in the concentration of bicarbonate and carbonate ions is up to 70%. Calcium and sulphate ions are reduced by up to 60% during liming, and further corrective treatment with  $H_2SO_4 + HEDP$  does not affect their content.

The content of suspended solids in the process of lime softening increases three times compared to the input water of the Styr River, further corrective treatment with  $H_2SO_4 + HEDP$  does not affect



Fig. 3. Change in water parameters during water treatment by liming, water treatment by liming and corrective treatment with  $H_2SO_4 + HEDP$  for 2022.

their concentration. The increase in TSS concentration may be due to the removal of the insoluble contact phase from the clarifier. Changes in the content of calcium ions and alkalinity change the nature of the dispersed phase formed during lime softening and it can be assumed that the formation of the dispersed phase during lime softening in the clarifier occurs with the formation of microdispersed particles with subsequent adhesion to sludge particles deposited in the clarifier from a supersaturated solution of Ca(OH)<sub>2</sub> lime. The microdispersed TSS fractions of water after lime softening are not precipitated in the clarifier, and in concentrations up to  $17-25 \text{ mg/dm}^3$  (Fig. 3) are supplied with the purified water from the clarifier, and the processes of further agglomeration of microdispersed particles into sludge particles in the cooling water system are not excluded.

The chemical composition of suspended solids in the Styr River water is determined by the content of organic matter up to 20%(OMLH), inorganic mass loss on heating (IMLH) and calcium carbonate up to 46% (IMLH + CaO) and silicon compounds up to 22%(SiO<sub>2</sub>), the chemical composition of suspended solids in water after water treatment by liming and corrective treatment with



Styr river water □ Water treatment by liming ■ Water treatment by liming and corrective treatment

Fig. 4. Change in water parameters chemical composition of TSS Styr River, water treatment by liming, water treatment by liming and corrective treatment with  $H_2SO_4 + HEDP$  for 2022 (OMLH—inorganic mass loss on heating at  $600\pm25^{\circ}C$  and IMLH—inorganic mass loss on heating at  $825\pm25^{\circ}C$ ).

Environment	Dange DCD of TCC um	Maximum particle size		
Environment	Range PSD of 188, µm	Size, $\mu m$	Quantity, %	
Styr water	0.5 - 50	10-20	79.0	
Water treatment by liming	0.5 - 100	20 - 30	80.5	
Water treatment by liming and corrective treatment with $H_2SO_4 + HEDP$	0.5-80	20-30	75.6	

TABLE 2. Characteristics of suspended solids particle-sizes' distribution.

 $H_2SO_4$  + HEDP is determined by the content of inorganic mass loss on heating (IMLH) and calcium carbonate up to 96% (IMLH + CaO) (Fig. 4). In the process of water treatment by liming and corrective treatment with  $H_2SO_4$  + HEDP, the chemical composition of suspended solids changes, the content of IMLH and CaO increases, which is due to the use of lime in water treatment, and the content of OMLH and silicon compounds decreases, which is due to their removal in the process of water treatment. Changes in the chemical composition of TSS in the process of water treatment indicate the removal of incoming TSS from the Styr River water with the formation of a new heterogeneous phase in the clarified water, consisting mainly of calcium carbonate.

Changes in the Dispersion Composition of Suspended Solids during Water Treatment. For the water of the Styr River, TSS is a finely dispersed particle with a fraction size of  $0.5-50 \mu m$ , with a maximum content of up to 78% of the fraction size of 10-20  $\mu$ m; for water treatment by liming, TSS particles are a fraction size of 0.5-100  $\mu$ m, with a maximum content of up to 80.5% content of fine and medium dispersed fraction of  $20-30 \ \mu\text{m}$ ; for water treatment by liming and corrective treatment with  $H_2SO_4 + HEDP$ , there are particles with a fraction size of  $0.5-80 \ \mu\text{m}$ , with a maximum of 75.6% content of fine and medium dispersed fraction of particles  $20-30 \ \mu\text{m}$  (Table 2, Fig. 5). In the process of water treatment by lime softening, a change and increase in the PSD of TSS is observed, taking into account changes in the chemical composition of TSS (Fig. 5), it can be stated that new particles are formed that are decisive in the formation of the total TSS content, from the distribution diagrams of Fig. 3, a, b in the size range up to  $0.5-5 \mu m$ , we can observe residual fine particles of water from the Styr River that do not settle in the clarifier during lime softening. The use of stabilization treatment with acid dosage during lime softening occurs with partial dissolution of the dispersed phase (Table 2), which is accompanied by a decrease in the particle size of the dispersed phase, total hardness, and an increase in the content of the  $SO_4^{2-}$ .



Fig. 5. Diagram of particle distribution (*a*—water of the Styr River; *b*—water treatment by liming; *c*—water treatment by liming and corrective treatment with  $H_2SO_4 + HEDP$ ).

In the water of the Styr River and in the process waters of the Rivne NPP, in the process of water treatment, a change in their qualitative structure is noticeable with a change in particle size (Fig. 6).

Microdispersed particles in the water of the Styr River quantitatively exceed large particles, amorphous particles, and irregular in



Fig. 6. Structure of suspended solids (*a*—water of the Styr River; *b*—water treatment by liming; *c*—water treatment by liming and corrective treatment with  $H_2SO_4 + HEDP$ ).

shape (Fig. 6, a). For the particles of Rivne NPP process water in the process of corrective treatment, there are large particles close to regular crystals in shape, surrounded by particles of a small fraction (Fig. 6, b, c). This observation can confirm that microcrystals play a crucial role in the further aggregation of particles and are coagulation aggregates of other fractions, their further aggregation in the cooling water, and it can be assumed that the further rate of agglomeration of the crystalline phase in cooling systems is affected by the speed of movement, mixing, and temperature. The shape of the water particles after lime softening and lime softening with  $H_2SO_4 + HEDP$  correctional treatment differs (Fig. 6, b, c), with the crystals being smaller and more spherical in the case of liming with correctional treatment, which can be explained by the process of formation of the carbon dioxide gas phase when using  $H_2SO_4 + HEDP$  correctional treatment with the decomposition of bicarbonate and carbonate ions.

Depending on the authors and the experimental conditions, prenucleation (nanometre-sized) clusters  $CaCO_3$ , dense liquid phases solid amorphous clusters of various sizes and compositions, crystalline particles and spinodal decompositions have been invoked either singly or in combination to give a multistep pathway [30]. That these larger clusters are thermodynamically stable and, with increasing supersaturation, can aggregate to form an amorphous phase [31], which explains the results of our research on increasing the nanometre-sized to micrometre-sized of particles.

Removal of Suspended Solids from Water after Water Treatment by Filtration. In accordance with water quality requirements, lime softening provides water purification from calcium ions, bicarbonate and carbonate ions, and the requirements for compliance with the standardized value of no more than  $10 \text{ mg/dm}^3$  in the treated water, the TSS content is not reproduced (Figs. 5, 6), which requires additional treatment methods. Since the design filtration of Rivne NPP's additional cooling water is provided for using VSMP-2000 filters with a pore size of 50 µm and a maximum particle fraction of 20–30 µm (Fig. 5, Table 2), no particles are removed. When using filtration on filters with a pore size of 40 µm and 20  $\mu$ m, TSS removal efficiency of 20% and 70% is achieved, respectively (Table 3). With applying filtration on filters with a pore size of 20 µm, an acceptable efficiency is achieved, which ensures a TSS content of no more than  $10 \text{ mg/dm}^3$  and can be the base for the industrial reconstruction of the filtration system for additional cooling water at Rivne NPP.

Protecting the safety of a nuclear power plant cooling water source is an emerging issue. Due to the diversity and complexity of the objects of cooling water source protection, there are still many

**TABLE 3.** Characteristics of TSS removal efficiency in water after treatment by liming and corrective treatment with  $H_2SO_4$ +HEDP (*n* = 12).

Indicator	M (min-max)	$\pm m$	$C_v$	Efficiency of removal, %
TSS initial, mg/dm <sup>3</sup>	17.3 (15.4–24.3)	2.5	11.8	_
TSS after filtering the filter pore size of the filter of 40 $\mu m,~mg/dm^3$	13.8 (11.5 $-15.6$ )	1.8	9.3	20
TSS after filtering the pore size of the filter of 20 $\mu m,\ mg/dm^3$	5.2 (5.0–5.5)	0.2	4.5	70

Note: *M* is the arithmetic mean of the results;  $\pm m$  is the standard error of deviation; min, max is the minimum and maximum values in the sample;  $C_v$  is the coefficient of variation.

cooling water problems that have not yet been addressed by mature technical methods. Strengthen technical support for water filtration equipment in lime softening water treatment for cooling water source protection, optimise and promote the development of scientific and technical innovation in cooling water source protection, well help filtration system with the pore size of the filter 20  $\mu$ m is more expensive to implement, but can remove up to 70% of TSS in the make-up water.

### **4. CONCLUSION**

The formation of suspended particles in purified water during liming and corrective treatment with  $H_2SO_4 + HEDP$  was studied. Lime softening provides water purification for the main components that form scale: a decrease in the concentration of bicarbonate and carbonate ions is up to 70%, calcium ions up to 60%, compared to the input water, and an increase in their concentration is observed for TSS, up to  $17-25 \text{ mg/dm}^3$ . In the process of treatment by liming and corrective treatment with  $H_2SO_4 + HEDP$ , a change in the chemical composition of suspended solids is observed, and simultaneously with the change in the chemical composition, the size and morphology of the particles change, the suspended solids become larger and the crystal structure of the particles appears. The resulting solid particles aggregate to form an amorphous phase, which explains the results of our studies on the increase in particle size from nanometre to micrometre as a result of water treatment. Changes in the chemical and particle size distribution of suspended particles indicate the formation of new particles that are crucial in the formation of the total TSS content in treated water during lime softening. Taking into account the results of determining the TSS concentration and their PSD, a filter material with pores of 20  $\mu$ m was selected, which allows separating up to 70% of particles and reducing the TSS content. The results of the study on particle aggregation during water treatment confirm the aggregation of particles and do not exclude their further aggregation and deposition in the cooling system water. Further research can focus on the study of the processes of formation and changes in suspended solids in the cycles of the cooling system and the impact of suspended solids in the cooling system return water, when discharged into a water body.

## REFERENCES

- Z. Lu, D. Mishra, K. Zhang, B. Perdicakis, D. Pernitsky, and Q. Lu, *Wat. Res.*, 200: 117202 (2021); https://doi.org/10.1016/j.watres.2021.117202
- M. Nasrollahzadeh, S. M. Sajadi, M. Sajjadi, and Z. Issaabadi, Interface Science and Technology, 28: 1 (2019); https://doi.org/10.1016/B978-0-12-813586-0.00001-8
- A. Celen, A. Çebi, M. Aktas, O. Mahian, A. S. Dalkilic, and S. Wongwises, *International Journal of Refrigeration*, 44: 125 (2014); https://doi.org/10.1016/j.ijrefrig.2014.05.009
- X. Ba, J. Chen, X. Wang, Hao Xu, J. Sun, Y. Qi, Y. Li, J. Wang, and B. Jiang, *Desalination*, 553: 116481 (2023); https://doi.org/10.1016/j.desal.2023.116481
- J. Li, Z. T. How, C. Benally, Y. Sun, H. Zeng, and M. G. El-Din, Sep. and Pur. Tech., 313: 123484 (2023); https://doi.org/10.1016/j.seppur.2023.123484
- 6. A. Vahedi and B. Gorczyca, *Wat. Res.*, **45**, Iss. 2: 545 (2011); https://doi.org/10.1016/j.watres.2010.09.014
- D. J. Venegas-Garcia and L. D. Wilson, *Materials*, 16: 655 (2023); https://doi.org/10.3390/ma16020655
- P. N. Kuznietsov, O. O. Biedunkova, and O. V. Yaroshchuk, Prob. At. Sc. and Tech., 2: 144 (2023); https://doi.org/10.46813/2023-144-069
- 9. B. Elduayen-Echave, M. Azcona, P. Grau, and P. A. Schneider, Journal of Water Process Engineering, 38: 101657 (2020); https://doi.org/10.1016/j.jwpe.2020.101657
- P. M. Kuznietsov and O. O. Biedunkova, Journal of Engineering Sciences, 10: 2 (2023); https://doi.org/10.21272/jes.2023.10(2).h1
- 11. A. P. Mathews, Journal of Environmental Management, 293: 112888 (2021); https://doi.org/10.1016/j.jenvman.2021.112888
- 12. T. Yadai and Y. Suzuki, Clean Water, 6: 7 (2023); https://doi.org/10.1038/s41545-023-00226-0
- R. Angelico, A. Ceglie, J.-Z. He, Y.-R. Liu, G. Palumbo, and C. Colombo, *Chemosphere*, 99: 239 (2014); https://doi.org/10.1016/j.chemosphere.2013.10.092
- 14. I. Labban, C. Liu, T. H. Chong, and J. H. Lienhard, J. Mem. Sc., 521: 18 (2017); https://doi.org/10.1016/j.memsci.2016.08.062

- M. Suthar and P. Aggarwal, J. R. Mech. and Geot. Eng., 10, Iss. 4: 769 (2018); https://doi.org/10.1016/j.jrmge.2017.12.008
- M. Scholz, Water Softening. Wetlands for Water Pollution Control. 2<sup>nd</sup> Edition (Elsevier: 2016), Ch. 17, p. 111–114; https://doi.org/10.1016/B978-0-444-63607-2.00017-4
- 17. P. Kuznietsov and O. Biedunkova, Nucl. and Rad. Saf., 1: 97 (2023); https://doi.org/10.32918/nrs.2023.1(97).04
- P. Kuznietsov, A. Tykhomyrov, O. Biedunkova, and S. Zaitsev, Scientific Horizons, 12: 25 (2022); https://doi.org/10.48077/scihor.25(12).2022.69-79
- Z. Ma, L.-F. Ren, D. Ying, J. Jia, and J. Shao, *Chemosphere*, **310**: 136929 (2023); https://doi.org/10.1016/j.chemosphere.2022.136929
- 20. A. Waza, K. Schneiders, J. Heuser, and K. Kandler, *Atmosphere*, 14: 700 (2023); https://doi.org/10.3390/atmos14040700
- H. Bagheri, H. Hashemipour, and S. Ghader, Comp. Part. Mech., 6: 721 (2019); https://doi.org/10.1007/s40571-019-00257-w
- 22. L. Bergwerff and L. A. Paassen, *Crystals*, **11**: 1318 (2021); https://doi.org/10.3390/cryst11111318
- J. Adusei-Gyamfi, B. Ouddane, L. Rietveld, J.-P. Cornard, and J. Criquet, Wat. Res., 160: 130 (2019); https://doi.org/10.1016/j.watres.2019.05.064
- 24. J. A. Nason and D. F. Lawler, *Wat. Res.*, **43**, Iss. 2: 303 (2009); https://doi.org/10.1016/j.watres.2008.10.017
- 25. B. Coto, C. Martos, J. L. Pena, R. Rodriguez, and G. Pastor, *Fluid Phase Equilibria*, **324**: 1 (2012); https://doi.org/10.1016/j.fluid.2012.03.020
- S. Feng, M. Yao, S. Guo, J. Lin, Z. Ao, C. Yu, K. Li, C. Xun, L. Yang, and J. He, Ch. Eng. Sc., 262: 118053 (2022); https://doi.org/10.1016/j.ces.2022.118053
- 27. A. E. Nielsen, Journal of Crystal Growth, 2: 289 (1984); https://doi.org/10.1016/0022-0248(84)90189-1
- V. Lahoussine-Turcaud, M. R. Wiesner, and J. Bottero, Journal of Membrane Science, 52, No. 2: 173 (1990); https://doi.org/10.1016/S0376-7388(00)80484-6
- M. F. Hochella, Earth and Planetary Science Letters, 203, No. 2: 593 (2002); https://doi.org/10.1016/S0012-821X(02)00818-X
- Vuk Uskoković, Nanotechnologies: Technology in Society, 29, No. 1: 43 (2007); https://doi.org/10.1016/j.techsoc.2006.10.005
- H. Komiyama, Y. Yamaguchi, and S. Noda, *Chemical Engineering Science*, 59, Nos. 22-23: 5085 (2004); https://doi.org/10.1016/j.ces.2004.09.025
- 32. C. L. Freeman and J. H. Harding, *Journal of Crystal Growth*, **603**, No. 2: 126978 (2023); https://doi.org/10.1016/j.jcrysgro.2022.126978
- D. Gebauer, M. Kellermeier, and J. D. Gale, Chemical Society Reviews, 43, No. 7: 2348 (2014); https://doi.org/10.1039/C3CS60451A