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EVALUATING THE IMPACT OF DISPERSED PARTICLES IN THE WATER OF A POWER PLANT RECIRCULATING COOLING SYSTEM ON THE DISCHARGE OF SUSPENDED SOLIDS INTO A NATURAL WATER BODY

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The object of this study is the processes of formation and changes of dispersed particles in fresh, make-up, cooling, and return water in open recirculating cooling systems (RCS) with an assessment of the influence of suspended substances in discharge waters on the aquatic ecosystem. The study was carried out on the example of the Rivne Nuclear Power Plant (RNPP) and the Styr River. Dispersed particles (DPs) pose technological obstacles in the RCS of power plants, and their content in discharge waters determines the ecological quality of water bodies. This paper describes the results of studying the formation and changes of DP in raw, make-up, cooling, and return waters of RNPP RCS with an assessment of the impact of suspended substances in discharge waters on the aquatic ecosystem of the Styr River. It was found that the formed dispersed particles after water treatment by liming contain DP consisting of calcium carbonate and have a size of 10–30 μm. As a result of agglomeration of DP in RCS, they aggregate to 120–150 μm, and due to low sedimentation resistance (sedimentation time 0.97 h), they settle in RCS. As a result of the deposition of DP in RCS, their significant decrease in return water (min–max=7.31–16.12 mg/dm^3) is observed, despite the increase in their content in make-up water after water treatment (min–max=10.22–49.46 mg/dm^3). According to the ecological classification, according to the content of suspended substances, the water of the Styr River in the zone of influence of RNPP discharges belongs to the II class, category 2, which characterizes the quality of the water as "very good" in terms of its state, and "clean" in terms of its degree of purity. It was concluded that the content of suspended solids does not exceed the established maximum permissible concentration (25 mg/dm^3), the increase in the concentration of suspended solids does not exceed the established ecological standard of 0.25 mg/dm^3 and does not have a negative impact on surface water. The results of the research could be used for other power plants equipped with an open RCS

Keywords: discharge return water, granulometric and chemical composition, suspended substances

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1. Introduction

Open recirculating cooling systems (RCS) of power plants are necessary for heat removal [1]; thermal loads from cooling water are released into the atmosphere through cooling towers, and return water is discharged into reservoirs [2]. The reliability of RCS from the point of view of the chemical aspect is related to the probability that the system will not fail due to chemical processes [3], the manifestations of operational failures are symptoms of the main influencing factors: chemical composition, temperature, pressure [4]. In addition to equipment failures in the RCS system, the chemical aspect determines the efficiency, productivity, and cost-effectiveness of operation [5], in particular, the implementation of proper chemical monitoring of process waters can increase the reliability of equipment and prevent the shutdown of power plants [6]. Make-up water is constantly sent to RCS and return water is discharged into the reservoir [7], the chemical composition for most components is calculated as a function of evaporation, blowing, and droplet removal [8], but this function is not preserved for dispersed particles (DP) [9]. DPs enter the RCS with make-up water, their formation also occurs in RCS due to the formation of sediments of the main components of water: calcium ions and carbonate, sulfate, and phosphate ions [10]. Costs to avoid scaling and anti-scaling treatment can be as high as USD 0.93 million per year or 0.88 % of revenue for a 550 MW base plant [11]. In order to effectively control the formation of sludge and scale in RCS, it is necessary to understand the processes of the behavior of DP in the RCS of power plants [12–14]. Common sources of DP in RCS are impurities in make-up water, which is used to replenish losses in the system; corrosion and erosion of structural materials; biological fouling; therefore, to determine the sources of entry, it is necessary to establish the chemical composition of DP.

According to their origin, DPs of substances in water bodies can be natural or man-made [15]. The composition of river runoff is dominated by silty particles with a size of 1–10 microns and silty particles with a size of 10–100 microns [16, 17]. In accordance with established environmental standards for insoluble substances, the indicator of suspended substances is determined [18–20], which characterizes the volume of impurities retained on a paper filter during sample filtration. Suspended substances have a great impact on hydrobionts and their habitat, and it consists in the fact that they can clog the gills of fish and prevent gas exchange [21], they also envelop eggs and interfere with their development: the eggs seem to dry out, and the embryo dissolves [22]. The negative side effect of suspended substances occurs through the reduction of feed resources and is caused by a decrease in the intensity of photosynthesis due to a decrease in water transparency [23]. Suspended substances, settling to the bottom, form sediments that prevent the development of benthos and the root system of plants [24].

The current paper reports a study into the processes of formation and changes of DP in RCS and the influence of their discharge with the return waters of RCS. Technological (processes of water preparation and concentration in RCS) and ecological (ecological standards of discharge and reservoir quality) aspects of the study are relevant both from the point of view of optimization of electricity production processes, and from the point of view of the impact on the environment.

2. Literature review and problem statement

On the basis of environmental safety standards for water use, water quality assessment for water use is carried out based on sanitary and hygienic standards. According to the existing concept of environmental regulation, the standard determines the ecological safety of water use with the provision of hygienic standards for maximum permissible concentrations (MPC) of pollutants in natural objects.

Pollution is the accumulation of unwanted solid substances on the heat transfer surface, the constant accumulation of pollution leads to an increase in thermal resistance and worsens the efficiency of operation of power plant equipment [25]. The process of pollution formation in RCS occurs with the crystallization of calcium carbonate ($CaCO_3$) and magnesium hydroxide ($Mg(OH)_2$). It is important to establish the chemical composition of pollution at industrial facilities, as it can explain the process of its formation and, accordingly, take measures to minimize it [26]. The importance of studying DP in RCS is emphasized by investigating the processes of formation of the heterogeneous phase of $CaCO_3$ [27–29]. The processes of $CaCO_3$ crystallization and inhibition of its formation by phosphonates were studied, and changes in the crystalline form of $CaCO_3$ were noted [27]. Heterogeneous nucleation and growth of $CaCO_3$ crystals was studied in supersaturated solutions [28]; it was shown that the forcing and further growth of crystals is reflected through the formation of seed crystals. It was shown [29] that the growth of DP crystals occurs due to their aggregation. However, the issues related to conducting research on the formation of the heterogeneous $CaCO_3$ phase on real objects, in particular during the formation of scale in RCS, remained unresolved since available studies [27–29] related only to model solutions and bench studies. It is obvious that the unresolved issue of research on real objects is due to insufficient effective cooperation between science and industry [30]. Known modern studies are focused separately on the study of the morphology, granulometric composition, chemical composition of DP of insoluble substances that occur under the influence of technological factors, or studies into the ecological impact of DP directly in a natural reservoir. The reason for the unsolved problems of the integrated approach may be objective difficulties associated with the lack of implementation of a holistic solution since it requires taking into account environmental and technological aspects, and accordingly, the cooperation of specialists from various fields. Thus, the formation of DP in the RCS of power plants may have a detrimental effect on system efficiency, equipment life, and environmental compliance. An option to overcome the relevant difficulties may be to carry out a comprehensive study of the formation of DP, taking into account ecological and technological aspects.

In [31], the results of studies of the effect of DP on increasing the formation of scale in RCS are given; however, there are some gaps in the study of the influence of dispersed particles of substances on the formation of scale. To reduce the processes of scale formation in RCS, water treatment by liming is used, which is an inexpensive method of water treatment of make-up RCS water [32]. At the same time, the wide application of liming for water treatment remains limited. According to paper [33], this is due to the fact that liming creates an excessive amount of sediment and introduces make-up components into the treated water, and therefore requires research into the mechanisms of heterogeneous phase formation. A corresponding attempt was made in work [34], which shows the possibility of directly determining the size of DP from images and indirectly from their sedimentation, which allows the use of microscopic and sedimentation methods to study the characteristics of DP during liming in water treatment. Other studies of sedimentation kinetics during liming are also known, but studies of the process of formation of DP during the industrial application of liming in clarifiers remain unresolved in them. For example, in works [33, 35] it was established that liming increases the concentration of suspended substances, thereby affecting the quality of make-up water and can increase the amount of pollution in the sewage treatment plant.

Study [36] shows that as the mixing speed increases, it is possible to consistently reach a state of DP equilibrium, when all particles precipitate, or partially precipitate, and the rest are kept in suspension, or all particles are suspended. According to the authors, the state of equilibrium of DP in RCS determines their content in the return waters that are discharged into the water body. It also emphasizes the importance of research in view of the need to study the ecological aspect of water discharge of suspended solids. The authors of paper [37, 38] noticed that the content of suspended substances in river water is determined by natural factors, in particular, it depends seasonally on water levels with the difference between the periods of their low and high marks, with a lower concentration during high water levels and a greater one during the period low water levels. However, in these works there are no data on the influence of natural factors of the content of suspended substances on the quality indicators of make-up water that has undergone liming and is used in an industrial facility. It is known that when the concentration of suspended substances increases due to anthropogenic pollution, this can lead to changes in the physical, chemical, and biological properties of a water body, as well as negatively affect its ecological state. Thus, according to the results of research [39], physical changes of negative environmental impact may include a decrease in light penetration, changes in temperature and levels of reservoir filling, which provokes biological changes: a decrease in the number, clogging of the food spectrum, and a decrease in the growth rates of hydrobionts. Despite the presence of partially unsolved issues, the fact is obvious that in order to avoid the negative environmental impact of suspended substances of anthropogenic origin on water bodies, their content should be strictly controlled during water discharge from industrial facilities.

Thus, DPs contribute to an increase in total suspended solids in return water, and elevated levels can lead to regulatory compliance issues and may require more frequent water treatment. All this allows us to state that it is necessary to conduct research on reducing pollution in RCS to ensure the economy, efficiency, and reliability of operation of the equipment of consumers of cooling systems with the provision of ecological discharge standards and the absence of impact on the water body. So, based on the existing problems of unresolved issues with setting up and conducting research for a real industrial object of RCS power plant with the interrelationship of technological and environmental aspects, conducting the research presented below has scientific and practical value.

3. The aim and objectives of the study

The purpose of our research was to determine the processes of formation and changes in the water level in the technological cycle of the power plant with an assessment of the impact of return discharge water on the water body. The practical value of the study is the possibility of applying the proposed approaches to power plants that have the same type of RCS to implement measures to minimize the water discharge of DP with return waters.

To achieve the goal, the following tasks were set:

– to identify regularities and evaluate changes in the actual content and chemical composition of DP over the multi-year observation period (2013–2022);

– to determine the morphological characteristics, particle size composition, and settleability of dispersed particles with the identification of mechanisms of formation and changes in the properties of DP;

– to carry out an ecological assessment of the impact of DP discharge with return water on a water body (according to the indicators of the maximum permissible concentration (MPC), the dynamics of the permissible increase in concentration and the maximum permissible discharge (MPD) of suspended substances), to establish the factors that shape the volume of DP inflow to reservoirs.

4. The study materials and methods

The water treatment system and RCS at the Rivne Nuclear Power Plant (RNPP) and water in the Styr River, in the zone of influence of water discharges from the RNPP, were chosen as the object of this study. Water treatment of make-up water in RNPP RCS is carried out by repurification with liming agent in clarifiers under bicarbonate mode and corrective treatment with oxyethylidene diphosphonic acid (OEDF) and sulfuric acid. Water after water treatment is filtered on high-speed mesh mechanical filters with a filter cell size of 50 microns. RCS return water is discharged into the Styr River through one outlet, without treatment.

Research hypothesis assumes that during water treatment by liming, the formed DPs are not completely deposited in the clarifiers, which is why they enter the RCS with make-up water. It is assumed that compliance of the DP content with ecological standards in return waters is the result of their deposition and accumulation in the RCS. The research was carried out by experimental study of technological processes and did not require simplification as it contains the results of actual measurements.

The morphology of dispersed particles (DP) was determined using a binocular microscope XS-5520 LED (China) and a scanning electron microscope Tescan Vega 3 LMU (Czech Republic). Granulometric composition of DPs – by obtaining the dependence of their number distribution using a laser particle counter HIAC/ROYCO 8000A (USA).

The chemical composition of DPs was determined according to recommendations from [40]. Sample preparation involved the separation of DP by filtering with the help of "blue" tape filters. The samples were calcined at 600±25 °C to determine the loss on calcination of organic substances (OMLH) and at 825±25 °C to determine the loss on calcination of carbonate substances (OMLH). The mass fraction of the components was converted to the content in oxides.

Determination of the settling time of DPs (t, h) was carried out by the standard gravimetric method under the influence of gravitational forces [41]; settleability (W, %) was determined by the difference in concentrations of suspended substances before and after settling (1):

$$W=100\cdot(C_0-C_1)/C_0, \quad (1)$$

where C_0 is the initial concentration of suspended substances before precipitation, mg/dm^3; C_1 is the concentration of suspended substances after the end of the time of complete sedimentation, mg/dm^3.

The selection of water samples was carried out in accordance with DSTU ISO 5667-6:2009, the quantitative content of DPs was determined by the concentration of suspended substances, which was determined by the gravimetric method [42] when filtering water samples through a "blue" tape filter. All measurements were carried out by the certified measuring laboratory at RNPP.

The ecological assessment of Styr River water in the area affected by water discharges was carried out by the method of comparing actual values with MPC according to [19, 20] and determining the ecological status of surface waters [43] (Tables 1, 2).

Statistical treatment of the research results involved determining the range of data series (min–max), arithmetic mean (M), standard deviation (SD) of the corresponding sample and statistical analysis of data using the Minitab software package (Version 21.4.1, Minitab, LLC) (USA) .

Table 1

Environmental classification of surface water quality [44]

Water quality class	I	II		III		IV	V
Category	1	2	3	4	5	6	7
Suspended solids, mg/dm^3	<5	5–10	11–20	21–30	31–50	51–100	>100
Names of classes and categories of water quality according to their state	Excellent	Good	Satisfactory		Bad		Very bad
	Excellent	Very good	Good	Satisfactory	Medium	Bad	Very bad
Names of classes and categories of water quality according to the degree of their purity	Very clean	Clean	Polluted		Dirty		Very dirty
	Very clean	Clean	Quite clean	Weakly polluted	Rather polluted	Dirty	Very dirty

Table 2

Hygienic requirements for the composition and properties of water in water bodies at points of economic-drinking and cultural-domestic water use for suspended substances

Indicators of the composition and properties of water in a water body	Categories of water use	
	For centralized or non-centralized household drinking water supply, as well as for water supply of food enterprises	For swimming, sports and recreation of the population, as well as water bodies within the boundaries of settlements
Suspended substances	The content of suspended substances during water discharge should not exceed:	
	0.25 mg/dm^3	0.75 mg/dm^3
	For water bodies containing up to 30 mg/dm^3 of natural mineral substances, an increase in the content of suspended substances within 5 % is allowed:	
	MPC – 25 mg/dm^3	

5. Results of research on dispersed particles

5. 1. Characteristics of quantitative content and chemical composition of dispersed particles

The Styr River in the area of RNPP water intake is characterized by years of low and abundant water. Low values of water consumption are observed in August–September, high values during floods in spring periods of the year in March–April. The actual water consumption of the Styr River for 2013–2022 varied in the range from 10 to 63 m^3/s with M=27 m^3/s, SD=18 m^3/s. The actual volume of flow rate for refueling RNPP RCS from the Styr River depends on the season and is up to 2.63 m^3/s in warm and up to 1.56 m^3/s in cold periods of the year. For the researched period of 2013–2022, the costs of feeding RNPP RCS from the Styr River are M=1.68 m^3/s, SD=0.41 m^3/s. The return water consumption of RNPP RCS ranges from 15–22 % relative to recharge costs up to 0.65 m^3/s in the warm and up to 0.37 m^3/s in the cold periods of the year, which for the studied period of 2013–2022 is characterized by the values of M= 0.31 m^3/s, SD=0.22 m^3/s.

The concentration of DP in the water of the Styr River before water intake and after discharge in 2013–2022 varied in the range of min–max=6.44–14.35 mg/dm^3, M=11.35 mg/dm^3, SD=2.44 mg/dm^3 (Fig. 1).

The concentration of DP in make-up water that underwent pre-treatment by liming and corrective treatment (OEDF and H_2SO_4) in 2013–2022 varied in the range of min–max=10.22–49.46 mg/dm^3, M=27.46 mg/dm^3, SD=13.85 mg/dm^3 and had no seasonal dynamics of changes. The concentration of DP in cooling water for which concentration processes occur as a result of evaporation and aeration in cooling towers of RCS in 2013–2022 varied in the range of min–max=17.31–27.85 mg/dm^3, M=20.52 mg/dm^3, SD=5.44 mg/dm^3, in return water of RCS min–max=7.31–16.12 mg/dm^3, M=12.44 mg/dm^3, SD=3.11 mg/dm^3.

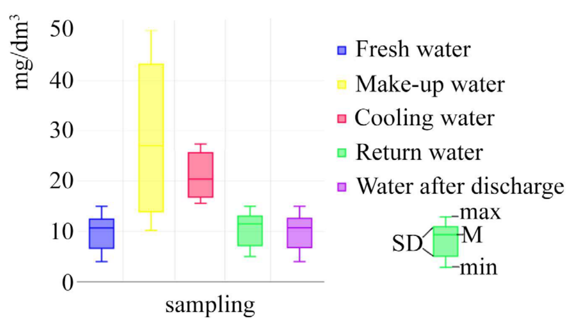


Fig. 1. Concentration of dispersed particles in technological waters of the cooling system at the Rivne nuclear power plant and water in the Styr River

The chemical composition of DP in the Styr River water is determined by the content of organic matter up to 20 % (OMLH), inorganic mass loss during heating (IMLH) and calcium carbonate up to 51 % (IMLH+CaO) and silicon compounds (SiO_2) up to 22 %. The chemical composition of make-up water is determined by the content of IMLH and calcium carbonate up to 78 % (IMLH+CaO) (Fig. 2).

Also, in the cooling water the content of IMLH and calcium carbonate decreases to 68 % (IMLH+CaO), in the return water it further decreases to 50.4 % (IMLH+CaO), and the content of OMLH increases to 25 % and SiO_2 to 15 %.

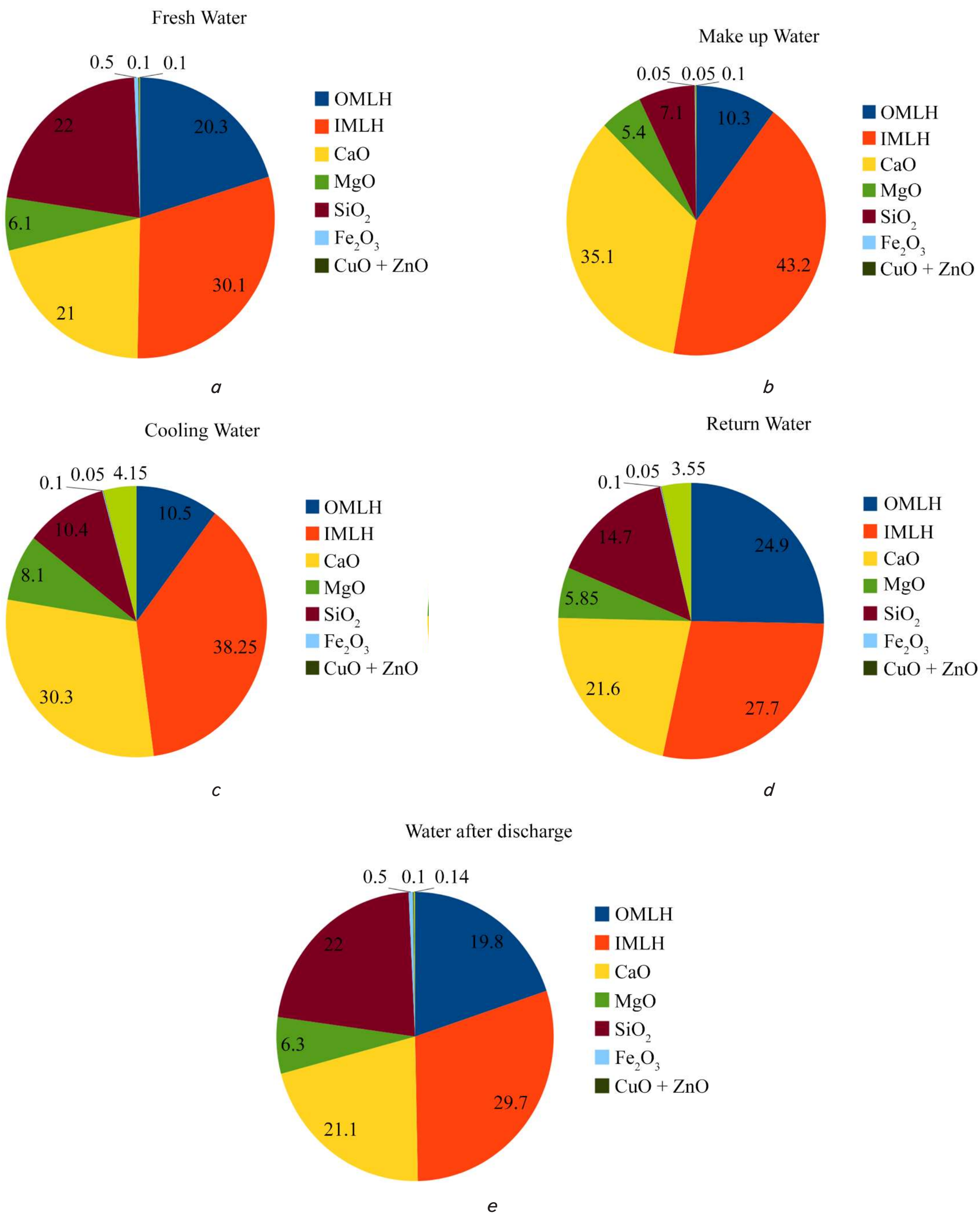


Fig. 2. The chemical composition of dispersed particles in the technological waters of the cooling system at the Rivne nuclear power plant and water in the Styr River: *a* – water to the water intake; *b* – make-up water; *c* – cooling water; *d* – return water; *e* –water after discharge

5. 2. Characteristics of morphology, granulometric composition, and sedimentation of dispersed particles

Microscopy of DP of process waters of RNPP RCS and water in the Styr River were obtained using Tescan Vega 3 LMU and XS-5520 LED, which made it possible to visually highlight the crystalline structure of DPs and their higher content in make-up water (Fig. 3, 4). Also, visual methods of research made it possible to notice that the deposition of DP in RNPP RCS occurs with the formation of two types of deposits: scale and soft sludge deposits (Fig. 5).

According to the data above, it can be determined that during liming, the granulometric composition changes with the formation of new fractions of the heterogeneous phase of DP. The maximum particle size observed in RCS water is 120–150 μm, the smallest size for the incoming water of the Styr River is 2–10 μm, for clarified water the maximum content of the fraction is 10–30 μm (Table 3).

The sedimentation properties of DP in the process waters of the cooling system at RNPP, determined by the settling time (t) and settleability (W), demonstrate the shortest time (0.97 h) and the highest settleability (78.3 %) for DPs in cooling water (Table 4).

Table 3

Granulometric composition of suspended solids in process waters at RNPP RCS and in the water of the Styr River

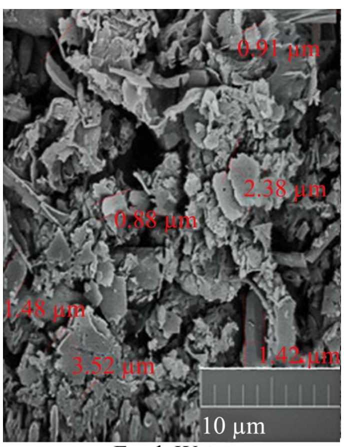
Environment	DP fraction, μm	Maximum fraction	
		Size, μm	%
Raw water	0.5–20	2–10	79.0
Make-up water	20–50	10–30	80.5
Cooling water	50–150	120–150	83.6
Return water	20–50	20–50	75.3
Styr river water after discharge	0.5–20	2–10	79.5

Table 4

Results of studies on determining the settling time and settleability of DPs in the process waters at RNPP RCS

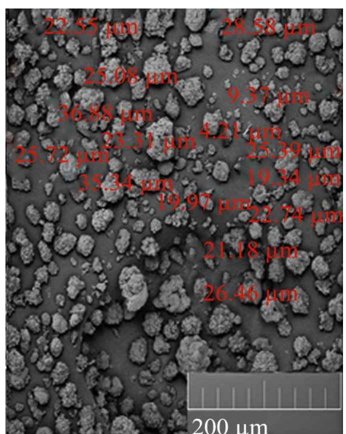
Environment	t, h	$C_0\pm\Delta$*, mg/dm^3	$C_1\pm\Delta$*, mg/dm^3	W, %
Make-up water	6.63	36.21±5.54	12.22±2.96	66.3
Cooling water	0.97	24.35±3.44	5.27±1.56	78.3
Return water	5.63	11.82±2.78	8.86±2.03	25.0

Note: Measurement error according to the procedure for measuring the content of suspended solids*



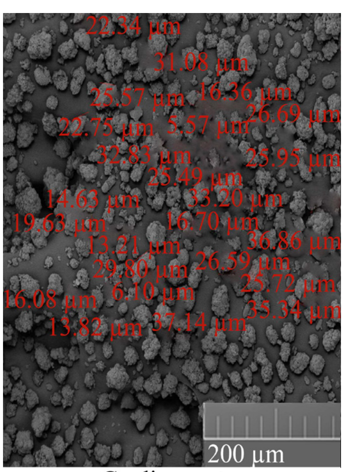
Fresh Water

a



Make-up water

b



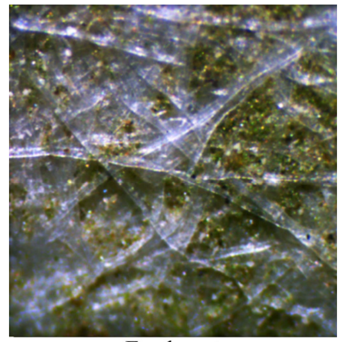
Cooling water

c

Return water

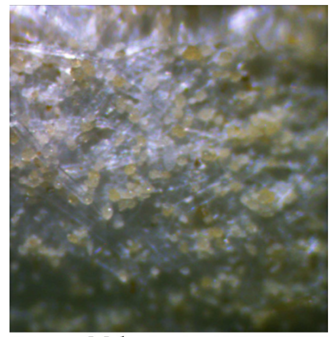
d

Fig. 3. Morphology of dispersed particles in process waters: *a* — water in the Styr River before intake; *b* — make-up water; *c* — cooling water; *d* — return water) of the cooling system at the Rivne nuclear power plant



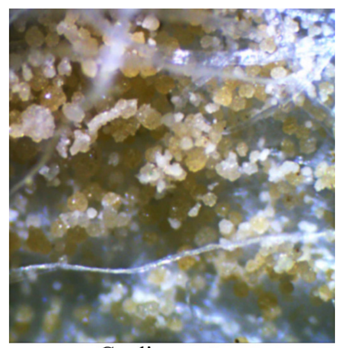
Fresh water

a



Make-up water

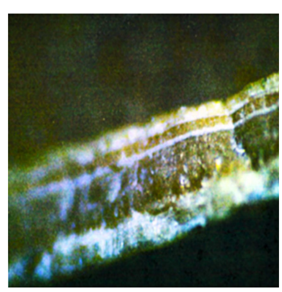
b



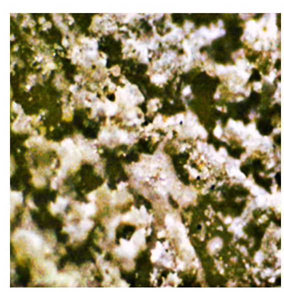
Cooling water

c

Fig. 4. Photographs of dispersed particles in technological waters: *a* — water of the Styr River before intake; *b* — make-up water; *c* — cooling water; *d* — return water of the Rivne nuclear power plant cooling system (magnification 20x)



a



b

Fig. 5. Photographs of deposits in the cooling system at the Rivne nuclear power plant: *a* — solid carbonate deposits formed as a result of scale formation processes; *b* — sludge deposits formed as a result of the deposition of dispersed particles

In waters of the Styr River and the technical waters of the cooling system at RNPP during the water treatment process, there is a noticeable change in the morphology of DPs (Fig. 3–5) with a change in the size of the particles (Table 3). The longest sedimentation time was measured for make-up water (6.63 h), and the lowest sedimentation was measured for return water (25 %) of the RNPP cooling system (Table 4).

5. 3. Ecological evaluation of discharges of dispersed particles with return waters

In terms of the content of suspended solids, wastewater at the RNPP's wastewater treatment plant meets the hygienic requirements for the composition and properties of water in water bodies (Table 2). The increase in the concentration of suspended solids as a result of the water discharge of RNPP RCS for 2013–2022 was in the range of min–max=0.058–0.206 mg/dm^3, M=0.137 mg/dm^3, SD=0.047 mg/dm^3 (Fig. 6) and did not exceed the rated value of the increase in the concentration of suspended substances during water discharge of 0.25 mg/dm^3.

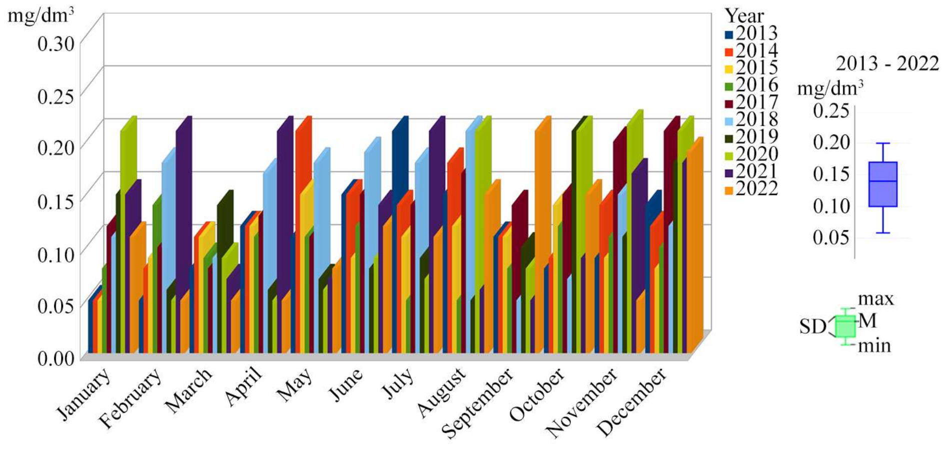


Fig. 6. Increase in the concentration of suspended substances due to the water discharge of the return water in the cooling system at the Rivne nuclear power plant for 2013–2022

The value of suspended solids in the return waters at RNPP RCS and the water of the Styr River after the RNPP water discharge does not exceed MPC and is up to 0.4 MPC (Fig. 1, 6). According to the ecological classification of suspended substances, water in the Styr River after the water discharge at RNPP belongs to the II class, category 2, which characterize the water quality in terms of its condition as "very good"; the degree of purity – "clean".

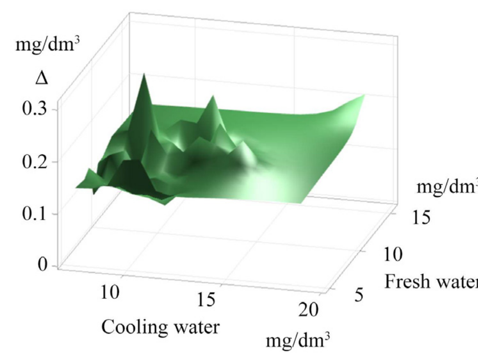
A correlation dependence was built (Fig. 7, *a*), which determines the content of suspended substances in the water of the Styr River after the discharge of return water from RNPP RCS, depending on the background concentration of suspended substances in the raw water of the Styr River before the water intake at RNPP.

The dependence that determines the content of suspended solids in the Styr River water in raw water before the water intake and after the discharge of the return water of the cooling system of the Rivne nuclear power plant reveals a statistically significant (p<0.001) direct correlation at the level of very strong with *r-Pearson*=1.00 and *R–sq*=99.82 % (Fig. 7, *b*) and is described by equation (2):

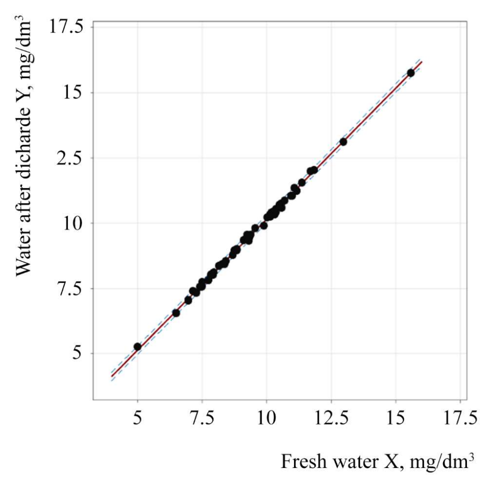
$$C_c=0.08341+1.007\cdot C_b, \qquad (2)$$

where C_b is the background concentration of suspended substances in the raw water of the Styr River, mg/dm^3; C_c is the concentration of suspended substances in the Styr River water after discharge of return water, mg/dm^3.

For RNPP, according to requirements [45], the maximum permissible discharge (MPD) is 6825 kg/year per power unit. The actual values of the discharge of suspended solids with the return water at RNPP RCS for 2013–2022 were in the range of min–max=1105–1524 kg/year per power unit, M=1457 kg/year per power unit, SD=105 kg/year per power unit. The actual values of the discharge of suspended solids did not exceed the normalized value of MPD, the mass share of the actual discharge of suspended solids is up to 22 % of MPD.



a



b

Fig. 7. Correlation dependence: *a* – the increase in the concentration of suspended substances (Δ) depending on concentration in the cooling water and water in the Styr River before the water intake; *b* – concentrations of suspended substances in water of the Styr River after the discharge (*Y*) and before the water intake (*X*)

The comparative characteristics of the concentration of suspended substances for the RNPP are comparable to other NPPs, which may indicate the identity of the processes of changes in the concentration of suspended substances in RCS (Fig. 8). Similar structural changes with their thickening and subsequent sedimentation can explain the rather low values of the concentration of suspended substances in the return water at other nuclear power plants (Fig. 8).

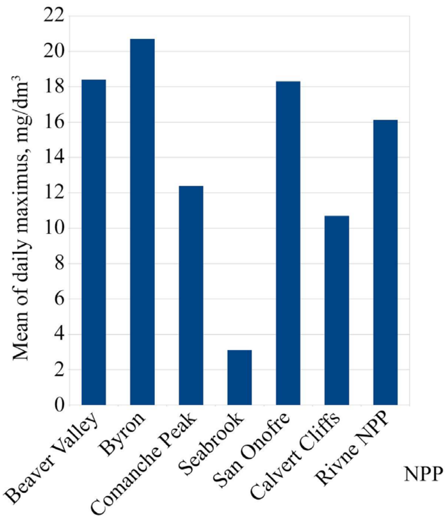


Fig. 8. Comparative characteristics of suspended solids discharges based on average content values for daily maximums at nuclear power plants

As a result, there is a decrease in the concentration of suspended solids due to precipitation of DPs (more than 50 μm) in the return waters at RCS, compared to their concentration in the make-up and cooling waters. The established sedimentation process allows one to ensure compliance with the MPC of suspended solids in the Styr River water (25 mg/dm^3) after the discharge of return water from RNPP RCS and the rated difference in the content of suspended solids in the discharged water (0.25 mg/dm^3).

6. Discussion of results of investigating dispersed particles in the water of an open recirculating cooling system at the power plant

The content of DPs in the Styr River water depends on the water levels in the river, with a lower concentration during high water levels and a higher concentration during the period of low water levels [37]. The detected fluctuations in the concentration of suspended solids in the Styr River (Fig. 1) confirm studies reported in [37, 38], which explain such changes by the effect of natural factors on the content of suspended substances in surface waters. The results of our studies show that seasonal fluctuations in DPs in the Styr River water do not affect the content of DPs in the supplementary water at RNPP RCS and depend on the processes of water treatment by liming (Fig. 1).

The technology of liming in clarifiers tends to increase the content of DP compared to the values for fresh water (Fig. 1), which is also noted in studies [34, 35]. The increase in the content of DPs, compared to the values for fresh water, is explained by the presence of heating, which reduces the dissociation of lime $Ca(OH)_2$. In the cooling water in RCS at RNPP, the content of DP decreases (Fig. 1), which determines the processes of the formation of the heterogeneous $CaCO_3$ phase according to [27–29]. As the speed of mixing, turbulence, and residence time in RCS increases, the effect of precipitation on DPs increases, which reflects the described equilibrium of $CaCO_3$ precipitation in the solution [36], and, subsequently, leads to a decrease in their concentration in the return water (Fig. 1).

For DPs in make-up and cooling water, there is a change in the chemical composition of DPs, namely, a decrease in the content of organic substances, silicon compounds, and an increase in the content of calcium compounds (Fig. 2). The detected change in the chemical composition during water treatment confirms the limitations of liming as this process introduces make-up components into make-up water [33]. Changes in the chemical composition of DPs in the water treatment process indicate the removal of DPs in the Styr River water with the formation of a new heterogeneous phase in the make-up water during liming, consisting mainly of $CaCO_3$. Subsequently, a recirculating change in the chemical composition is observed in RCS, which is due to the processes of scale formation in RCS. The chemical composition of DPs of the return water at RNPP RCS and water in the Styr River differ (up to 5 %) in terms of OMLH and SiO_2 content, however, the volume of water discharge in the amount of M=1.68 m^3/s does not affect the chemical composition of DPs in the water of the Styr River since the content of DP components before water intake and after discharge is comparable (Fig. 2).

The formation and change of DPs in process waters determines the processes of their sedimentation in turbulent flows during heating in consumer heat exchangers, cooling, evaporation in cooling towers and concentration in RCS. These processes determine the agglomeration of DPs (Fig. 3, 4), and taking into account the maximum fraction of DP in the return water (Table 3), processes of their agglomeration occur. The formation of DPs during water treatment, obtained from the results of research at a real industrial facility, RNPP (Fig. 3, 4, Table 3), is confirmed by experimental studies of DP aggregation during liming [33] and sedimentation [27–29]. The determined insignificant time of deposition of DP in RCS (Table 4) confirms their sedimentation and deposition in RCS. The absence of agglomerated DPs larger than 50 μm in the return water (Table 3) indicates the predominant deposition of the large main fraction in the cooling water of RCS (120–150 μm, 83.6 %), which confirms the research hypothesis.

Deposition of particles with a size of more than 50 μm is observed in the form of sludge (Fig. 5, *b*). The fact of the formation of sludge deposits confirms the previous research reported in [45] since the formation of solid dense deposits in the form of scale occurs from soluble components of the carbonate system. The detected shortcoming from the accumulation of DP in the form of sludge deposits in RCS can be leveled by its systematic mechanical removal during planned and preventive repairs of power units of power plants.

It should be noted that the discharge of suspended substances with return water is one of the important standardized discharge indicators and is included in all permits for water discharge of nuclear power plants in the amount of 1000–10000 kg/year per power unit [46]. The obtained correlation dependence (Fig. 7) and the dependence equation (2) can be used to predict and limit the discharge of suspended substances with return waters of RCS.

This research could be used to understand the processes of formation and behavior of DPs in RCS at other power plants. The methodology used in the monitoring of suspended solids can be used for the ecological assessment of discharges with the identification of negative factors of the discharge of suspended solids of power plants into a water body. Monitoring and environmental assessment of discharges is important for safe, reliable, and efficient operation of power plants [47, 48].

The limitation of the method of the current research may be the determination of the characteristics of nano-sized DPs, which is complicated by the use of existing instrumental methods. This is because the methods used in our study may not provide sufficient resolution or accuracy to measure nanoscale DPs. The behavior of DPs is accompanied by aggregation processes, which can affect their settleability, so another limitation of this study is the application of the results for waters that do not contain dispersants.

The development of this research may involve further studies into the possibility of using dispersants as a reagent for corrective treatment of RCS. Dispersants contribute to the splitting and dispersion of DPs and prevent their agglomeration, which could make it possible to abandon the systematic mechanical cleaning of RCS from sludge. However, the ecological assessment of discharge, in the case of dispersant application, may have different results since it will affect the settleability and retention of DPs in the form of a suspension. That is, the further development of the research also requires a comprehensive approach with an assessment of technological and environmental factors.

7. Conclusions

1. During clarification by liming, the volume of DPs increases by an average of 2.4 times, and their chemical composition changes with an increase of calcium carbonate to 27 % and a corresponding decrease in organic substances and silicon compounds. A change in the granulometric composition was also noted, in particular, the particle size increased from 2–10 μm in raw water to 10–30 μm in the make-up RCS water. The application of filtration of make-up water that has undergone liming on high-speed mesh mechanical filters with a filter cell size of 50 μm does not make it possible to completely remove the formed dispersion phase due to the high dispersion of particles and significant volumes of RCS feeding needs.

2. Formed DPs after liming, as well as seed crystals of calcium carbonate, are aggregated to 120–150 μm, and due to low sedimentation resistance, they are deposited in RCS. The heterogeneous phase at the available temperatures in RCS does not form a dense scale but settles in the form of sludge, which causes the need for systematic cleaning of the hydrotechnical structures in RCS from sludge.

3. As a result of the precipitation of DPs in RCS, their decrease is observed by 1.34 times in the cooling water, compared to make-up water, and by 1.64 times in the recirculating, compared to the cooling water of RCS. According to the ecological classification for suspended substances, RNPP wastewater belongs to the II class, category 2, which characterizes the quality of the water as "very good" in terms of its condition, and "clean" in terms of its degree of purity. That is, the content of suspended solids does not exceed the established MPC and does not exert a negative impact on the environment.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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