

# INTEGRAL METHODS FOR CONTROL OF COMPLEX PROCESSES IN NPP COOLING SYSTEMS

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DOI: <https://doi.org/10.20535/2218-930032022266978>

*The relevance of the study is to ensure the reliable operation of NPP recirculating cooling water systems (RCWS) and select the method for discharge water conditioning. The purpose of the study is to provide scientific and technical substantiation of conditions that will effectively provide and improve the reliable and efficient long-term operation of NPP RCWS equipment. The study included analysis of main factors that influence the efficient and reliable performance of heat exchangers, and of modern scientific and technical approaches to study water-chemical regimes (WCR) of operating RCWS systems for preventing depositions of sparingly soluble salts and corrosion of power equipment, to study thermal-hydraulic regimes (THR) in RCWS WCR laboratory simulation, and to study the deposition rates on heat exchange surfaces (HES). The improvements refer to gas chromatography technique to control the content of oil product in water; the process flow diagram for the floor drain radioactive water treatment; methods of discrete control over RCWS operational efficiency with monitoring THR and WCR indicators, and deposition rates during laboratory studies and industrial tests. The obtained results make it possible to carry out a scientific and technical substantiation of the conditions for effective implementation of RCWS structural reconfigurations in order to increase the installed capacity factor (ICF) and for economical use of water during the variable loads on individual power units of large power facilities, considering their installed capacity, service life, and heat exchange equipment condition due to the use of separate RCWS with individual THR, WCR, and established individual standards for the amount of blowdown water and its possible reuse as makeup water for power units.*

**Key words:** chromatography, cooling, methods of control, oil, water

Received: 11 November 2022

Revised: 22 February 2023

Accepted: 24 February 2023

## 1. Introduction

The operating Ukrainian NPPs use recirculating cooling water systems (RCWS) of heat-exchange equipment with cooling lakes and evaporative cooling towers. Using RCWS with evaporative cooling of circulating water makes it possible to reduce NPP needs in fresh water by 50-80 times [1]. Such RCWSs have wide opportunities to further improve reliability and extend service life of power equipment due to conditioning of makeup water, conditioning of blowdown water for its reuse in NPP cycles, and

configuring RCWS with several cooling towers-condensers, heat exchangers into separate systems with individual thermal hydraulic regimes (THR), water chemistry regimes (WCR), and evaporation factors (Fe) [2]. Partial evaporation of circulating water in all RCWS types contributes to its mineralization and changes in physical and chemical characteristics, which results in precipitation of slightly soluble chemical compounds and more intensive formation of sludge on RCWS internal components, leads to their corrosion, erosion wear and biological fouling [3]. Safe mineral level of circulating

water in terms of preventing deposition on heat exchange surfaces is achieved by using makeup water and maintaining its quality, blowdown of circulating water, using scale and corrosion inhibitors, and other RCWS water chemistry measures [4, 5].

Conditioning methods currently used at thermal power plants (TPP) and nuclear power plants (NPP) are divided into mechanical methods (centrifugal filtration, ultrafiltration), ion transfer to slightly soluble compounds (liming, sodification, softening with carboxylic cation exchange resins, two-stage Na-cationization on strongly acid cation exchange resins), membrane methods (nanofiltration, reverse osmosis), oxidation (of chlorine, potassium permanganate); desalination (using anion and cation exchange resins, final purification with mixed filters, and distillation).

**Relevance:** NPP main performance indicators, which jointly determine electricity underproduction, include the efficiency factor (EF) and the installed capacity factor (ICF). In economically developed countries, the installed capacity factor reaches 93%. However in 2015 – 2019, the installed capacity factor at Ukrainian NPPs had an undesirable trend and decreased from 72.16% in 2016 to 68.34% in 2019 with a corresponding underproduction increase from 0,76 to 1,51...109 kWh. The main causes for underproduction at Ukrainian nuclear power plants included grid restrictions, standby mode, and forced shutdowns at some power units. Forced shutdowns, reduction of efficiency factor, and corresponding underproduction, which resulted in 15-20%, were caused by inefficient performance of condensers [2].

The main cause of reduced efficiency factors of Ukrainian NPPs and the

corresponding electricity underproduction is that the condenser vacuum is not sufficient for condensing exhaust steam leaving the turbine. The cooling system maintains the required level of vacuum, and its efficiency is ensured by low thermal resistance value, i.e. no deposits on heat exchange surfaces and good density of piping system. Degraded pipe density due to corrosion processes leads to cooling water in-leakages and condensate contamination. Deposit formation is driven by physical and physical-chemical conditions when crystals of slightly soluble compounds precipitate on the surfaces of heat exchange tubes from the cooling water solution. If pipe metal has a high corrosive activity in cooling water, deposits will have a combined corrosive and mineral origin [1].

The trouble-free operation of condensers at RCWS with evaporative cooling towers is ensured by using scale and corrosion inhibitors and control of evaporation factors, by rational use of stable blowdown, reasonably supplemented losses of circulating water, and use of conditioned blowdown water received after its treatment on hybrid water treatment facilities for other NPP cycles, etc. As a rule, RCWSs are designed with several cooling towers, a shared cooling water basin, and a complex of heat exchangers of different designs, which are made of steel and various copper / aluminum alloys having different corrosion resistance. However, it is not taken into account that aluminum alloys have a relative corrosion resistance in slightly acidic media, copper alloys - in acidic, neutral and slightly alkaline solutions, and steel alloys are characterized by corrosion inertness at  $\text{pH} > 9$ . In such systems, the efficiency of individual heat exchangers and cooling towers is leveled by averaging pH value, total salt

concentrations (SC), and evaporation factor in the circulating water system [6].

These shortcomings could possibly be corrected by replacing equipment (replace brass condenser pipes with stainless ones) and also by developing effective complex water chemistry regimes for I and II circuits, and for RCWS circuit of individual NPP units. This will help to save the consumption of makeup water; use blowdown water in a reasonable way; improve reliability and extend service life of power equipment [1, 7].

Relevant point is to reconfigure individual cooling towers of RCWS into various structural configurations with individual water chemistry regimes. Individual water chemistry of RCWS coolant can be connected in serial or parallel-serial systems. In this case, it becomes possible to ensure individual RCWS water chemistry of NPP units due to the feed water quality and blowdowns of individual units, grid load, operation life, condition of the condenser heat exchange surface, etc. Advantages of such unit configurations include wide opportunities to control individual RCWS water chemistry, as well as efficiency and reliability of the cooling system at reduced feedwater flow rates, maximum reuse of blowdown water after its selective conditioning at hybrid water treatment plants (HWTP). Conditioning of makeup water and blowdown cycles help to maintain the preset regulated quality of coolants. The blowdowns are regulated by the selected water chemistry regime and volume of the system, and if we speak about RCWS, the time of the year shall be taken into account too. The amounts of blowdown water from different systems range from 1% for steam generators to 3% for RCWS. The RCWS blowdown water (700 t/h per one 1000 MW unit, temperature 25...35 °C,

pH = 8.9...9.6) is oversaturated with hardness salts, has high concentrations of  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  ions. Obviously, blowdown discharges to the environment having such salt concentrations pose a significant threat of salinization and overheating to natural water areas and suppress their flora and fauna vital activity. On the other hand, RCWS blowdown water is a valuable raw material, which can be reused in RCWS or other NPP process cycles after additional conditioning [2, 8].

Physical and chemical control over effective NPP RCWS water chemistry includes control of ionic composition of circulating and makeup water, main physical and chemical indicators of cooling atmosphere (air), as well as condition of heat exchanger internal surfaces ("water - steam", "water - water", "water - oil"). The rate of deposit buildup  $J$  ( $\text{mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ) on heat exchange surfaces depends not only on the coolant ionic composition, but also on the specific surface of salt crystals, scale formers, which were formed during evaporation of dispersed medium, and the ratio of total crystal surface to the heat exchanger surface. The value of this indicator  $J$  responds to the volumes (doses) and chemical composition of scale inhibitors, which is not disclosed by manufacturers [1, 2].

I&C used to characterize RCWS performance at various water chemistry regimes and predict reliability for the long-term operation of RCWS equipment include the ability to determine the quality indicators of the aquatic environment, such as pH, conductivity  $\chi$  ( $\mu\text{S}\cdot\text{cm}^{-1}$ ), concentrations of impurities: sodium, chlorides, sulfate ions, iron, copper, magnesium, calcium, phosphates, oxygen, hydrogen, oil products, inhibitors, suspended solids, etc. [9].

Physical and chemical control of complex processes undergoing in NPP RCWS shall consider the influence of various natural, design, operational and many other factors that include pH and conductivity measurements, control of power machinery oil properties (density, viscosity, acid value, oxidation stability, vapor flash point, pour point, demulsification time, deaeration time, corrosion on steel rods and plates, content of water-soluble acids and alkalis, pH of aqueous extract, water content, content of mechanical impurities, industrial grade, sulfur content, additive content, sludge content, color), biological fouling, deposits, and corrosion on heat exchange surfaces, dispersed composition of sparingly soluble salt crystallization centers, etc. [1, 10].

Application of integral methods to control properties of all operating fluids used in the whole operation process of RCWS equipment (start-up, operation, shutdown, preservation) will permit to analyze the efficiency of RCWS equipment performance and determine further improvement measures.

Reliability of NPP power equipment largely depends on the aging processes in this equipment during operation, including RCWS operation [11, 12]. At the same time, the main goal of ageing management is to ensure safety and maximum operational efficiency by implementing technically and economically feasible measures and upgrades aimed at timely detection and mitigating within acceptable limits the ageing degradation of NPP components [13]. Practical experience of such ageing management during RCWS operation is of great importance for implementing lifetime extension measures for Ukrainian NPPs [14].

The paper [15] presents the analysis data of events that took place at Ukrainian

NPPs caused by aging processes, and those gained from national and international experience, including the operation of the main and auxiliary heat exchange equipment.

The main objectives of RCWS water chemistry are to provide makeup water treatment, regulate the amount and dispersibility of suspended matter, concentration of calcium, bicarbonate ions and free carbon dioxide, add chemicals into the circulating water to prevent buildup of scale and corrosion products in heat exchangers and service water supply systems [16]. At the same time, oil products and other organic substances are absorbed by deposits present on the internal surfaces of heat exchangers and reduce their efficiency [17]. The operating NPPs use RCWS, which differ in capacity, heat exchanger design, and cooling agent pressure [1, 17].

Normally, RCWS consists of a water cooler (cooling tower, spray pond, cooling lake), circulating water pumps, heat exchangers (condenser, oil cooler, etc.). If a cooling agent (power machinery oil, etc.) in RCWS of essential consumers (turbine building; reactor building) has an excessive pressure, it will get into the cooling water, thus deteriorating its quality. The cooling agent (clean steam, condensate) in RCWS of turbine condensers is under vacuum. Therefore, even an insignificant degradation of sealing in condenser components leads to circulating water entering the condensate ("in-leakage"). Its salt concentration (SC, g/dm<sup>3</sup>) is SC<sub>w</sub>=1.5 g/dm<sup>3</sup>, which is higher than in condensate (SC<sub>c</sub>=1...5 µg/dm<sup>3</sup>). A small "in-leakage" (30...40 dm<sup>3</sup>/h) of cooling water into the condensate leads to a sharp deterioration of its quality, which sometimes significantly exceeds the rated values [1].

Presence of oil products in the recirculating cooling water above the established standards deteriorates NPP RCWS water chemistry indicators, which affects the operational reliability of heat exchange equipment [2, 18].

Degraded sealing in heat exchanger components, e.g. surface condenser of NPP condensing plant, leads to condensate contamination. This occurs in the surface condenser where steam is condensed, and pressurized cooling water that contains oil product impurities, which exceed the established limits, gets into this condensate [1].

With NPP equipment in operation, the water in the Floor Drains Treatment System (SVO-3) and Laundry Drains Treatment System (SVO-7) is radioactive and can contain oil products along with dispersed particles [19, 20]. Moreover, floor drains may contain impurities of hydrocarbons, including oils - up to 5 mg/dm<sup>3</sup>; salt concentration - up to 5 g/dm<sup>3</sup>; coarsely dispersed particles - from 5 to 1000 g/dm<sup>3</sup>, particle distribution density from 0.1 to 1500 μm, and the total radioactivity value – up to 0,155 mCi/dm<sup>3</sup> [1, 21]. This requires controlling the content of oil products and radioactive compounds in such water during the treatment processes.

**Oil products found in circulating cooling water** can originate from treatment processes when the recirculating cooling water is prepared for its intended use [1, 11]. Mineral turbine oil is often one of the main oil products found in recirculating cooling water [1]. At the same time, turbine oil is normally acidic [22, 23]; pH and  $\chi$  water measurements may have errors caused by turbine oil film formed on the surfaces of sensors which measure these indicators [1]; oil products, including turbine oil, which are present in

cooling water, are absorbed by porous deposits formed on the internal surfaces of heat exchangers, and this will additionally reduce the heat transfer coefficient and heat transfer efficiency [1, 2]. So the urgent problem is to control the presence of mineral turbine oil in circulating cooling water and in the resulting condensates.

**Turbine oil can enter the circulating cooling water** via shell-and-tube heat exchangers (oil-to-water coolers). This occurs when there is sealing degradation in tube plates of these oil coolers. As a result, some turbine oil under pressure enters the circulating cooling water flow [1]. Condition monitoring of such oil coolers is an urgent problem and can be done by gas chromatography (GCh) methods which determine the content of turbine oil at the cooling water inlet and outlet sides of the oil coolers.

The paper [24] establishes the abilities and limitations of physical and chemical methods, including gravimetric method for determining oil products in water; systematizes information on instrumentation used for measuring oil products in water and standard samples for calibrating these instruments; and mentions the prospects for application of GCh methods. International Organization for Standardization approved only GCh method for determining the content of oil products in water, which allows identification of oil product composition and can be used as an arbitration method [25].

Water can get into turbine oil via oil-to-water coolers. This occurs when there is sealing degradation in tube plates of these oil coolers. As a result, some water under pressure enters the turbine oil flow, for example, during the shutdown of the oil cooler [1].

The study [26] describes techniques to control **water in oil products**, i.e. mineral insulating liquids for high voltage equipment, which are based on chemical, electrochemical, chromatographic and spectral methods of analysis. The fundamentals of these methods are visualization, volume measurement of gas released due to chemicals interaction between water and mineral oil, coulometric titration, coulometry with electrolysis on a sensing element, gas chromatography methods (GCh), including direct injection of mineral oil sample into the gas chromatograph vaporizer, non-vacuuming of mineral oil, equilibrium separation of dissolved water from mineral oil, injection of liquid mineral oil extract into the gas chromatograph vaporizer; as well as spectral test methods (IR spectroscopy, NMR spectroscopy, EPR spectroscopy, luminescence spectroscopy).

Prospects of using GCh methods for determining water in mineral oils are noted in [27].

The study [28] outlines methods to determine water in mineral insulating liquids and oil-impregnated paper and pressboard using an automated coulometric titration with Karl Fischer reagent. This method uses a dry nitrogen jet to separate water from a preset volume of insulating liquid, and then the water is separated from the nitrogen flow in the preset volume of Karl Fischer reagent in a special measuring coulometric cell. It can be used to determine water in mineral turbine oils. This method is characterized by generation of hazardous wastes.

The study [29] presents a mathematical model of mass-exchange processes related to extracting liquid from the analyzed sample of insulating liquid by a liquid extractant, which can be used to determine the content of oil

products in water. The mechanism of such liquid extraction process is detailed in [30].

All this demonstrates the relevance of problems to control the content of mineral turbine oil in circulating cooling water and in resulting condensates, and the content of water in circulating turbine oil. It can be controlled by using GCh methods for analyzing properties of coolant samples at cooling water inlet and outlet sides of oil cooler when determining the content of **turbine oil in recirculating cooling water**, and of oil cooler turbine oil when determining the content of **water in turbine oil**. This allows us to conduct the in-service inspection of heat exchangers, including oil coolers, without the need to shutdown them.

Thus, there is a need to further manage the **topical issue** of improving the long-term operation reliability and efficiency of NPP RCWS heat exchange equipment with the purpose to further increase the installed capacity factor and improve the economic use of water and mineral oils for power machinery by determining the content of mineral turbine oil in water and of water in mineral turbine oil.

This research study is devoted to the **topical issue** of improving the long-term operation reliability and efficiency of NPP RCWS equipment to increase the installed capacity factor and economic use of water by reconfiguring the total volume of RCWS coolant to individual RCWSs with individual THR and WCR considering the installed capacity, operation life of NPP units, condition of condensers, and grid load with adjusted and scientifically justified amount and quality of makeup water.

The **goal** of scientific research is to give scientific and technical substantiation of conditions that will effectively provide and

improve the reliable and efficient long-term operation of NPP RCWS equipment.

To achieve the goal, the following tasks need to be solved:

- Provide an analysis of main factors that influence the efficient and reliable operation of heat exchange equipment, and of modern scientific and technical approaches to the study of water chemistry regimes in place at operating RCWS systems;

- Conduct a THR research with laboratory simulation of RCWS water chemistry;

- Conduct a research of deposit forming rate on the heat exchange surfaces;

- Improve GCh technique for control of oil products in water;

- Improve the process flow sheet for floor drains radioactive water treatment;

- Improve the discrete control method for RCWS operational efficiency during automatic monitoring of THR and WCR indicators, deposition and corrosion rates to determine WCR efficiency by laboratory studies and industrial tests for waters with different salt concentration.

## 2. Materials and Methods

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**Study on transient processes in RCWS water chemistry regimes.** These studies require the development of physical and chemical control and selection of relevant physical and chemical indicators, which characterize the intensity of precipitation that results in scale formation from supersaturated circulating water and corrosion of power equipment. Determining recommended limits for evaporation factor (Fe) of circulating water provides conditions for RCWS reliable and long-term operation by maintaining optimal concentrations of carbonate and total

hardness salts and corrosion depolarizers, strong acid anions at preset RCWS water chemistry and circulation ratio. The complexity and large number of measured parameters of multistage RCWS do not allow making calculated predictions with the required accuracy and need experimental studies for each type of feed water and selected water chemistry regimes on a scaled model that reproduces thermal-hydraulic and chemical engineering aspects of industrial RCWSs. Experimental studies need to be conducted on a model of two or more stage RCWS with autonomous cooling towers, which corresponds to the water chemistry of the proposed flow chart configurations of the multistage RCWS. All this demonstrates the relevance of conducting laboratory research based on a scaled physical model of a cascade two-stage RCWS that meets the following basic requirements: main thermal-hydraulic characteristics (water and air velocities; specific heat loads; water, air, heat exchange surface temperatures, etc.) in the test bench elements (evaporative cooling towers, condenser, heat exchangers) that are identical to industrial plants. The test bench of scaled two-stage RCWS model with autonomous cooling towers has the ability to study, if necessary, both single stage and multi-stage RCWSs. The created test bench shall have instrumentation (I&C) for continuous monitoring of water and air flow rates, their temperature, pH and  $\chi$  values in individual stages of the scaled model. It shall have devices for studying the scale formation and corrosion rates; a complex of analog-to-digital converters for subsequent computer control of the test mode and computer archiving of its parameters. **The object of research** is methods for monitoring complex processes in NPP cooling systems. **The subject of**

**research** is physical and chemical characteristics of the studied fluid flows, water samples taken from the sampling points in the test bench of the RCWS scaled thermal hydraulic physical model, and steel samples of St. 20 grade.

Laboratory studies were carried out using water with different salt concentrations (the Dniester River:  $SC=450\text{...}550\text{ mg/dm}^3$ ; the Styr River:  $SC=250\text{...}300\text{ mg/dm}^3$ ; the Siverskyi Donets River:  $SC=650\text{...}750\text{ mg/dm}^3$ ) at preset specific heat fluxes in heat exchangers, continuous flow rates of working fluids in heat exchangers. The volume of water in scaled RCWS model was chosen considering continuous water makeup during the test. The volume of circulating water in the test bench model is determined by the sum of water flow rates through the equipment, as well as by water losses from the system for evaporation and blowdown. With water velocity of  $1,0\text{...}1,5\text{ m/s}$ , the water flow rate through the test bench model will be  $0,201\text{...}0,302\text{ dm}^3/\text{s}$  respectively. The total water flow rate ranges from  $0,380$  to  $0,570\text{ dm}^3/\text{s}$ . During the test,  $1\text{ dm}^3$  samples were taken for the analysis with 12 hour interval. The total volume of water taken for sampling during the test was  $36\text{ dm}^3$ , which corresponds to the specific water losses with blowdown, equal to 0,037% of the total water flow in the test bench model. During the 400 h test, the absolute evaporation flow rate was from  $493\text{ dm}^3$  to  $1478\text{ dm}^3$ . The circulation ratio of the recirculating water in RCWS can vary from 0,9 to 20,0. The process flow diagram of the improved test bench of RCWS scaled thermal hydraulic physical model (STHM) is shown in Fig. 1.

STHM test bench includes a TK-4L cooling tower (item 7) with a built-in partition

(item 20), a confusor (item 18), a film packing (item 8), a lid (item 17), two warm water coarse spray nozzles (item 9) over the "crossed disks" polyethylene layer of 38...39 mm in diameter; two recirculating water tanks (item 19) that receive water after it was treated in the cooling tower; two pumps (item 1); mechanical filter (item 3). The hydraulic schematic is equipped with required safety valves, bypass process lines, etc. All STHM parameters are selected based on complex calculations considering heat-transfer properties of the working fluids and preset temperatures of the studied surfaces. Improvement of STHM test bench included periodic water sampling downstream mechanical filters (item 3). PKZh-904A type instrument (not shown in Fig. 1) was used to control the diameter of suspended solids present in the water and water cleanliness. The tests demonstrated that diameter of suspended solids in water samples downstream mechanical filters (3), did not exceed  $5\text{ }\mu\text{m}$ , which was acceptable result for tests.

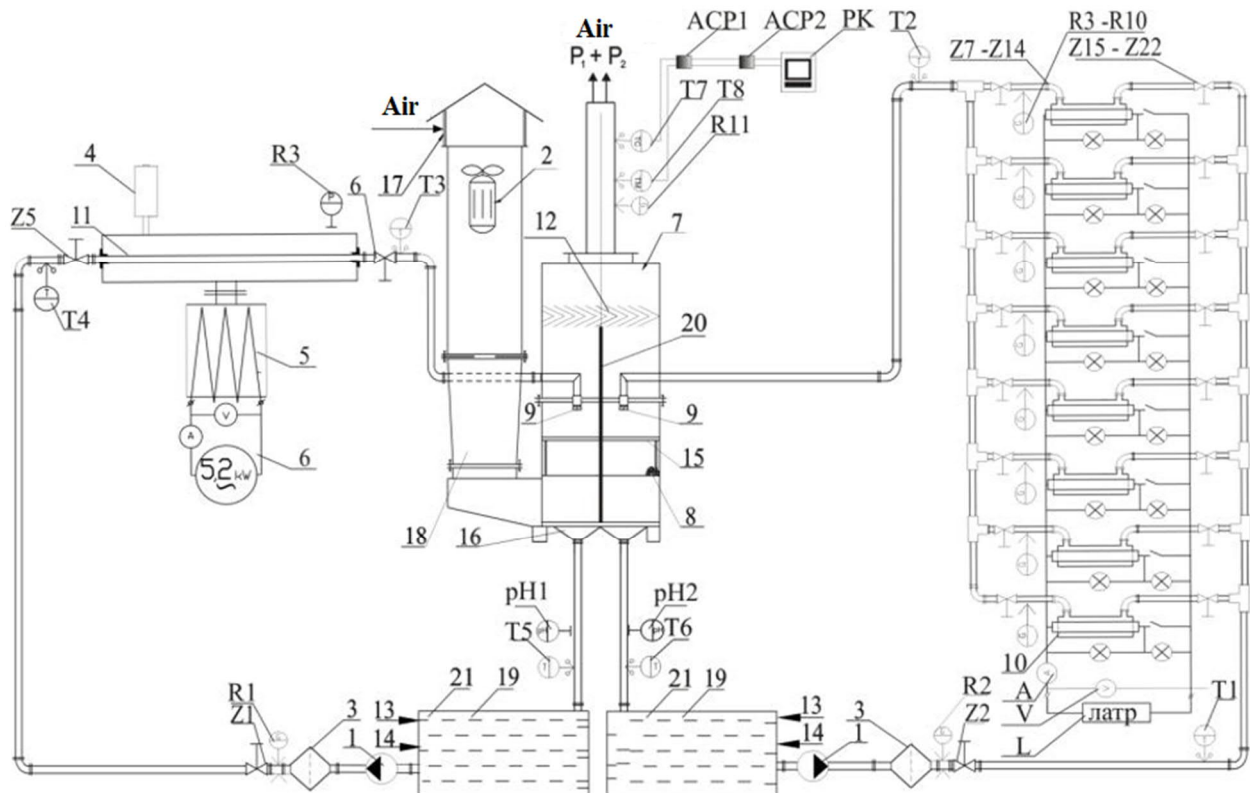
The following I&C and test equipment was used: TK-4L standard small-size cooling tower, SFI-800 water flow meters, SU-7001 and DPL-1P air flow meters, TSP-1187 resistance thermometers (temperature ranges from  $-50$  to  $500^\circ\text{C}$ ); AK-310 automatic conductivity meter; EV-74 conductivity meter, I-160MI laboratory ionometer. Fe calculations were made according to the procedure [2]. J values were measured according to the procedure [31]. PKZh-904A instrument was used to control the size of suspended solids in water.

#### **Improvements of GCh technique for control of oil product in water.**

The object of research is GCh technique for control of mineral turbine oil in water. The



subject of research is water samples containing oil product - TP-22S mineral turbine oil.



**Fig. 1.** Process flow diagram of STHM test bench for kinetic study of sludge formation on heat exchanger surfaces: 1 – circulating pump; 2 – fan; 3 – mechanical filter; 4 – safety valve; 5 – bypass lines; 6 – power supply to electrical heater; 7 – cooling tower; 8 – film packing; 9 – supporting grid; 10 – heat exchanger with external flow around the sample; 11 – heat exchanger with internal flow around the sample; 12 – drop catcher; 13 – makeup water; 14 – reagent dosage; 15 – horizontal perforated plate; 16 – pan; 17 – lid; 18 – vertical confusor; 19 – reservoir; 20 – partition; 21 – sampling point; Z1...Z22 – gate valves. I&C: R1...R11 – flow meters; T1...T8 – resistance thermometers; A – ammeter; V – voltmeter; PK – personal computer; ACP 1 – COM analog to digital converter; ACP 2 – USB analog to digital converter; L – laboratory electrical autotransformer; pH1-pH2 – pH meters

Crystal-2000M gas chromatograph with a vaporizer and a flame ionization detector was used to determine content  $C_i$  of turbine oil in water. The method involves extracting turbine oil from a water sample with an extractant (n-hexane), purifying the extract from polar compounds with a sorbent, analyzing obtained eluate in the gas chromatograph, summing up areas of hydrocarbon chromatographic peaks in the

range of retention times equal to and/or greater than n-octane ( $C_8H_{18}$ ) and computing the content of oil products in water according to the preset calibration relation. Chromatographic capillary column with a stationary dimethyl-polysiloxane phase has the following specifications: operating temperature not less than  $300^\circ C$ , inside diameter from 0,32 to 0,53 mm, length up to 30 m, and thickness of the stationary phase

film from 0,25 to 12  $\mu\text{m}$ . Measurable  $C_i$  concentrations of turbine oil in water range from 0,02 to 100  $\text{mg}/\text{dm}^3$ . With  $C_i$  concentrations exceeding 100  $\text{mg}/\text{dm}^3$ , the analyzed water sample is diluted with distilled water not containing oil products. Calibration mixtures of TP-22S turbine oil in water and n-hexane with concentrations ranging from 0,02 to 500  $\text{mg}/\text{dm}^3$  were used for calibrating the gas chromatograph. Tp-22s turbine oil quality indicators shall meet the fresh turbine oil requirements [22]. PKZh-904A liquid purity control instrument was used to determine the content of heterogeneous impurities in water: recorded size of heterogeneous particles ranges from 5 to 200  $\mu\text{m}$ , and if particle size exceeds 200  $\mu\text{m}$ , their sum is determined or the analyzed water sample is diluted with pure water, which does not contain any mechanical impurities.

### 3. Results and Discussion

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#### *3.1 Analysis of main factors affecting the efficient and reliable operation of heat exchange equipment and of modern scientific and technical approaches applied to the study of water chemistry regimes used in operating RCWSs*

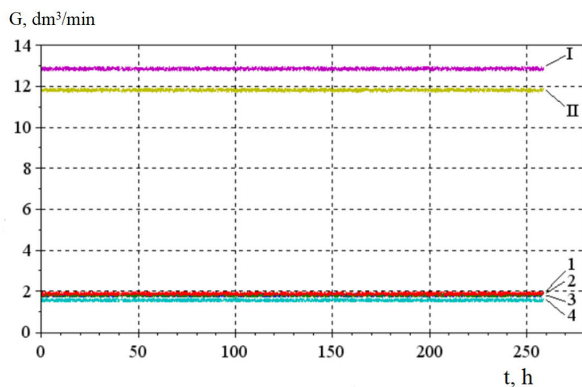
RCWS long-term operation can be ensured by effective water chemistry that sets the limits for circulating water evaporation, pH,  $\chi$ , Ht (total hardness), At (total alkali) values, etc., by dosing various scale and corrosion inhibitors that control the growth of corrosion and deposition of carbonate salts and corrosion products on heat exchange surfaces of power equipment [2, 6]. The level of knowledge about physical and chemical processes occurring in a thin film of coolant on heat exchanger surfaces is determined by the levels substantiating the selected THR and WHR for individual power units and their

structural configurations in RCWS, which can provide a long-term prediction of minimum corrosion and deposition rates on the heat exchange surfaces of power equipment, as well as its reliable operation [32]. Moreover, the knowledge about particle mass ratios of sparingly soluble calcium salts and iron oxides in the total deposition mass formed on the heat-exchange surface gives an opportunity to predict the corrosion rate and stabilization of deposition by using inhibitors and individual THR and WCR in NPP RCWS configurations and individual power units [33]. Generally at the production field, the thermal-hydraulic and water chemistry quality, changes in weather conditions (winter-summer) are analyzed at the end of the campaign, lasting up to 10 months of continuous operation, as well as during temporary shutdowns, and this, naturally, does not allow making operating changes in RCWS THR and WCR or conclusions on how specific temporary abnormalities of RCWS operational modes affect the processes of corrosion and deposition of sparingly soluble compounds on the heat exchange surface of power equipment [7]. In order to study the impact of different RCWS THRs and WCRs on the rate of deposits consisting of sparingly soluble carbonate salts of equipment corrosion products, and to develop monitoring of RCWS THR and WCR main performance indicators to assess the current condition of heat exchange surfaces in power equipment during the campaign and justify taking timely operator actions to decrease the intensity of corrosion and deposition processes ongoing on the internal surfaces of RCWS power equipment by correcting water chemistry indicators, it is required to conduct experimental study cycles on a scaled laboratory model that reproduces thermal hydraulic conditions of industrial plants under different water chemistry regimes in parallel

with large-scale tests at the industrial facilities [8].

### 3.2 THR studies on RCWS water chemistry laboratory simulation

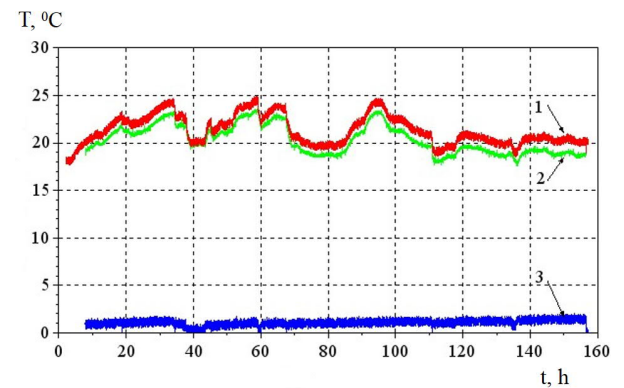
Laboratory studies were carried out on RCWS scaled thermal hydraulic model (STHM) with heat supply to monitored indicators (non-isothermal conditions) (Fig. 1). Fig. 2 shows the monitoring data of changes in thermal hydraulic indicators of RCWS working fluids in STHM air-cooled circuits with stable circulating water flow rate indicators (G), and specific heat flows in heat exchangers [7, 8].



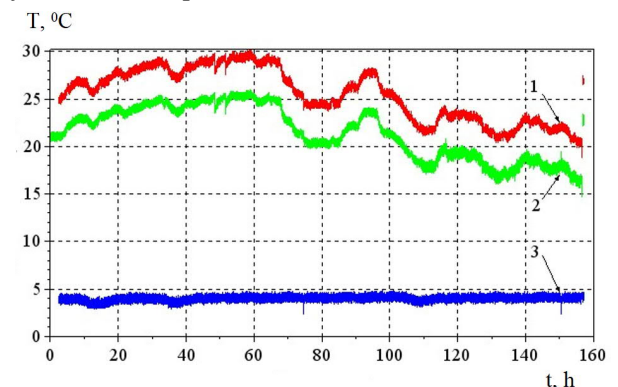
**Fig. 2** Circulating water volume flow rate indicators  $G$  in heat exchangers of the first and second stages: I - first stage; II - second stage (4 heat exchangers of the second stage); 1, 2, 3, 4 - individual heat exchangers of the second stage;  $G$  – circulating water volume flow rates,  $\text{dm}^3/\text{min}$ ;  $t$  – time,  $h$ .

Fig. 3...6 shows that during a relatively short time (160 h) the air temperature in RCWS cooling tower predictably changes by 5...15 °C. With longer periods of time, the temperature will possibly change by several tens of degrees. Based on results obtained from automatic monitoring of the working fluid thermal hydraulic indicators for a thermal hydraulic mode, it was established that this mode depends, in particular, on the

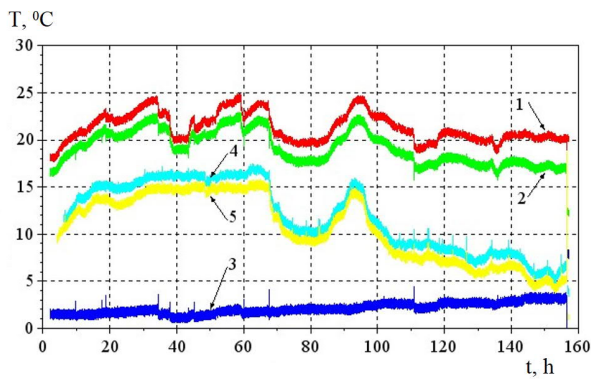
temperature and humidity of the atmospheric air.



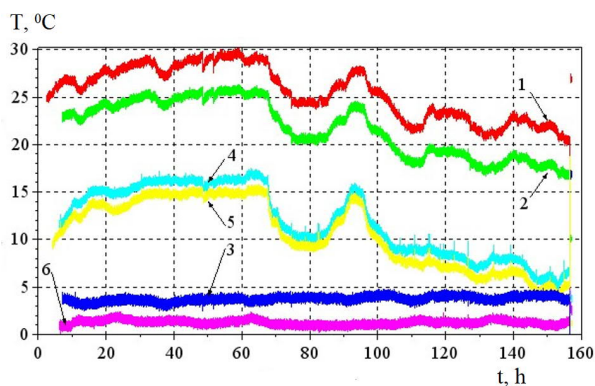
**Fig. 3** Temperature variation with evaporation of circulating water in circuit I: 1 - temperature variation with evaporation of circulating water in circuit I at the outlet of the heat exchanger with internal flow; 2 - temperature variation with evaporation of circulating water in circuit I at the inlet to the heat exchanger with internal flow; 3 - temperature difference at the inlet and outlet of the heat exchanger with internal flow;  $T$  – temperature, °C;  $t$  – time,  $h$ .



**Fig. 4** Temperature variation with circulating water evaporation in circuit II: 1 – temperature variation with evaporation of circulating water in circuit II at the outlet of heat exchangers with external flow; 2 – temperature variation with evaporation of circulating water in circuit II at the inlet to heat exchangers with external flow; 3 – temperature difference at the inlet and outlet of heat exchangers with external flow;  $T$  – temperature, °C;  $t$  – time,  $h$ .



**Fig. 5** Temperature variation with evaporation of circulating water in circuit I (cooling tower): 1 – temperature variation with evaporation of circulating water in circuit I at the outlet of the heat exchanger with internal flow (at the cooling tower inlet); 2 – circulating water temperature variation at the outlet of the first stage cooling tower; 3 – temperature difference at the inlet and outlet of the cooling tower. Air temperature indicators: 4 – wet bulb temperature; 5 – dry bulb temperature;  $T$  – temperature, °C;  $t$  – time, h



**Fig. 6** Temperature variation with evaporation of circulating water in circuit II (cooling tower): 1 – temperature variation with evaporation of circulating water in circuit II at the outlet of the heat exchanger with internal flow (at the cooling tower inlet); 2 – circulating water temperature variation at the outlet of the second stage cooling tower; 3 – temperature difference at the inlet and outlet of the cooling tower. Air temperature

indicators: 4 – wet bulb temperature; 5 – dry bulb temperature; 6 – wet bulb temperature and dry bulb temperature difference;  $T$  – temperature, °C;  $t$  – time, h

After long-term THR studies of RCWS I and II circuit waters with different salt concentrations evaporated to different Fe values (Fe = 3,5...4,0 for RCWS I and Fe = 6,5...7,0 for RCWS II), no changes in the temperature difference at the heat exchanger inlets and outlets were recorded due to thermal resistance effects of the formed deposits on the surface of metal test samples.

This is explained by the specific formation of sparingly soluble deposits on the studied surface looking like a thin discrete film (thickness  $\delta \approx 0,01...0,02$  mm [2]) and individual crystal formation nuclei of sparingly soluble salts, which do not affect the total thermal resistance value of the heat-exchange wall.

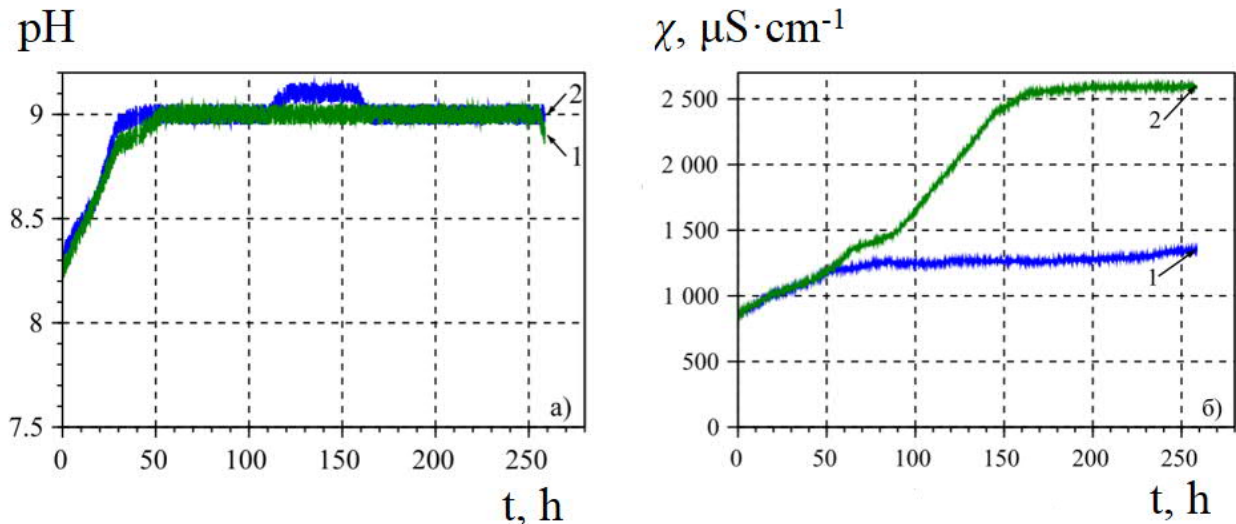
It has been proved that river water temperature influences the liming process and makeup water treatment [7, 8], as well as the cooling air temperature and humidity influence scale formation on the condenser heat exchange surface during the cooling and aeration of circulating water in the evaporative cooling tower.

Fig. 7 graphically shows the results of water chemistry studies on RCWS I and II circuits when feeding the scaled model system with makeup water from the Dniester River.

Lines 1 and 2 in Fig. 7 describe pH changes in untreated makeup water taken from the Dniester River from pH = 7,8...8,0, when evaporated to Fe = 3,5 and Fe = 6.0 respectively. The final process when pH value grows from  $\approx 8.2$  to  $\approx 9,0...9,2$  in the circulating water takes place during the same



period both for RCWS I circulating water with  $Fe = 3,5 \dots 4,0$ , and for RCWS II circulating water with  $Fe = 6,0 \dots 6,5$ , which is typical for evaporation of unstable river water with low hydrate alkalinity.



**Fig. 7** Variation of  $pH$  (Fig. 7-a) and  $\chi$  (Fig. 7-b) values with different  $K_e$  when evaporating the water from the Dniester River: 1 – RCWS I, first circuit; 2 – RCWS II, second circuit;  $pH$  –  $pH$  values;  $t$  – time,  $h$

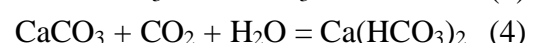
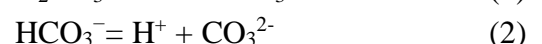
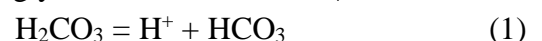
One of objective indicators related to water chemistry efficiency can be the time period passed from the recorded critical supersaturation in circulating water ( $F_{ss}$ ) and formation of sparingly soluble crystals in it, and their deposition on the studied surface of the test sample in the amount that is recorded by gravimetric method. It can be defined as the total latent time of scale formation process.

The use of  $pH$  and  $\chi$  values in circulating water allows us to compare physical and chemical indicators of the circulating water quality throughout the entire period of researches. These indicators characterize the influence of atmospheric carbon dioxide and evaporation factor on changes in physical and chemical composition of circulating and makeup water during their

The heat exchanger inlet and outlet circulating water temperature changes continuously throughout the day both in the 1<sup>st</sup> and 2<sup>nd</sup> STHM stages. The nature of temperature and time dependence in RCWS I and II circuits is the same.

aeration in the cooling tower. The beginning of latent period when massive crystallization of circulating water takes place can be recorded by changes in related physical and chemical water parameters when analyzing the automatic chemical monitoring databases throughout the whole research.

During evaporation, strong acid anions form soluble neutral compounds with  $Ca^{2+}$ ,  $Mg^{2+}$ , and  $Na^+$  cations, etc. Weak carbonic acid anions together with  $Ca^{2+}$  cation form a highly soluble bicarbonate  $Ca(HCO_3)_2$  and a sparingly soluble salt –  $CaCO_3 \downarrow$  [2].



It follows from the above that  $Ca^{2+}$  ion in supersaturated circulating water is in a

dissolved state represented as two salts:  $\text{Ca}(\text{HCO}_3)_2$  – a highly soluble calcium bicarbonate ionic compound, and  $\text{CaCO}_3$  – a sparingly soluble calcium carbonate ionic compound.

The pH value of  $\approx 9,1$  (Fig. 7) defines a significant concentration of bicarbonate ion which forms the  $\text{CO}_3^{2-}$  carbonate ion by the second stage dissociation, and then the sparingly soluble  $\text{CaCO}_3$  compounds, which tend to form deposits on the condenser heat exchange surfaces. Such pH values are critical for water chemistry system with high evaporation factors Fe and are characteristic for a system with low quality of unconditioned makeup water.

The complete dynamic stabilization process of the circulating water ionic composition will reach equilibrium when formation of sparingly soluble compounds  $\text{CaSO}_4$  and  $\text{CaCO}_3$ , as well as of highly soluble salts ( $\text{NaCl}$ ,  $\text{Na}_2\text{SO}_4$ , etc.) is completed.

The measured conductance of circulating water with stable Fe will be [7, 8]:

$$\chi = 10^3 \times (\sum(\lambda_{\text{HCO}_3^-} \cdot f_{\text{HCO}_3^-} \cdot C_{\text{HCO}_3^-}) + \sum(\lambda_i \cdot f_i \cdot C_i)) \quad (5)$$

Where:  $\lambda_{\text{HCO}_3^-}$ ,  $f_{\text{HCO}_3^-}$ ,  $C_{\text{HCO}_3^-}$  are equivalent conductance, activity coefficient, and equivalent concentration of  $\text{HCO}_3^-$  ion, respectively;  $\sum(\lambda_i \cdot f_i \cdot C_i)$  is the sum of products of equivalent conductance, activity coefficient, and equivalent concentration of ions that are in true soluble state.

The study of  $\text{pH} \approx f(\text{HCO}_3^-)$  and  $\chi = f(\text{SC})$  equilibrium establishing process demonstrated that pH with Fe = 3,0, and Fe = 6,0 in I and II circuits, respectively, under the preset thermal hydraulic circulation conditions reaches a stable pH value = 9,2 for almost the same time period from the start of

circulation in the system (30 h; Fig. 7). At the same time,  $\chi$  I with Fe = 3,5 reaches a stable value after 40...50 h, and  $\chi$  II with Fe = 6,0 after 150...160 h from the start of water circulation in the system. The delay in stabilization of  $\chi \approx f(\text{SC})$  value from  $\text{pH} \approx f(\text{HCO}_3^-)$  when circulation water reaches its preset regime is explained by instability in the carbonate system of untreated river water during its evaporation in STHM.

Unstable water is characterized by rapid supersaturation with  $\text{CO}_3^{2-}$  i  $\text{Ca}^{2+}$  ions, which are the main quantitative characteristics of  $\text{CaCO}_3 \downarrow$  precipitation.

A further  $\chi$  increase at the preset pH values occurs due to an increase in the ion concentration of highly soluble salts minus  $\text{Ca}^{2+}$  and  $\text{CO}_3^{2-}$  ions, which form sparingly soluble salt and will precipitate from the supersaturated solution. It reduces  $\chi$  value until the stabilization of Ca-carbonic acid equilibrium and a stable precipitation process from the supersaturated circulating water.

The stabilization period of the circulating water conductivity  $\chi$  is longer if compared to the stabilization period of circulating water by pH value according to the evaporation factor in (Fig. 7-b).

For comparison, Fig. 8 shows results of laboratory studies for RCWS I and RCWS II water chemistry regimes when using conditioned makeup water of the Styry River.

When the circulating water is evaporated, the supersaturation with  $\text{CO}_3^{2-}$  and  $\text{Ca}^{2+}$  ions occurs according to the previously described reactions. Formed  $\text{CO}_3^{2-}$  ions exceed values (the solubility product for calcium carbonate) by several times and precipitate from the solution. At the same time, precipitated  $\text{CaCO}_3$  causes a decrease in the deposition rate indicator (Fig. 8-b), corresponding to the value [7, 8].

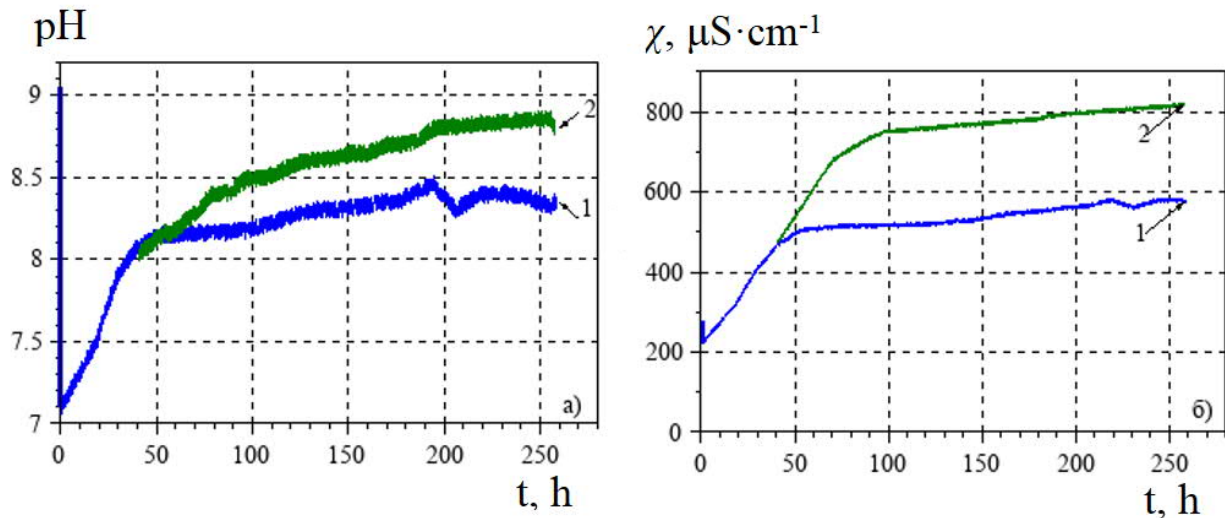


Fig. 8 Changes in pH (a) and  $\chi$  (b) values for different evaporation processes of the Styr River water: 1 – RCWS I, first circuit; 2 – RCWS II, second circuit; pH – pH value;  $\chi$  – conductivity,  $\mu\text{S}\cdot\text{cm}^{-1}$ ;  $t$  – time, h.

$$\Delta\chi = 10^3 \times \left( \lambda_{\text{Ca}^{2+}} \cdot f_{\text{Ca}^{2+}} \cdot C_{\text{Ca}^{2+}} + \lambda_{\text{CO}_3^{2-}} \cdot f_{\text{CO}_3^{2-}} \cdot C_{\text{CO}_3^{2-}} \right) \quad (6)$$

At the same time, due to other ions present in circulating water,  $\chi$  values in RCWS I and II circuits increase.

The pH value is stabilized after 50 hours of circulation, and ionic quasi-stability for other ions is achieved after 80 hours of circulation with consideration of  $\text{Cl}_c/\text{Cl}_m$  (where  $\text{Cl}_c$  is the concentration of chlorine ions in the circulating water;  $\text{Cl}_m$  is the concentration of chlorine ions in the makeup water) [2].

With stabilization of carbonic acid equilibrium in circulating water, the  $\chi$  indicator stabilizes with a slight delay after stabilization of pH value, which is characterized by the sum of  $\text{CO}_3^{2-} + \text{HCO}_3^-$  ions.

This delay period corresponds to the quality of limed water, which has not been stabilized on the clarifying filters ( $\Delta\chi = 50 \dots 80 \mu\text{S}\cdot\text{cm}^{-1}$ ).

$\Delta\chi$  (6) can be used to estimate  $\text{CaCO}_3$  crystallization rate from circulating water.

However, it is known that not all precipitated  $\text{CaCO}_3$  crystals are deposited on heat-exchange surface. Crystals formed from the supersaturated solution are crystallization centers of sparingly soluble salts where sediments are deposited alongside with heat exchange surface and are carried with blowdown water outside the heat exchanger.

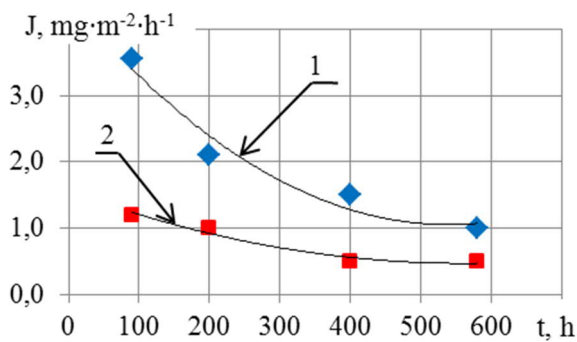
Integral surface of dispersed particles in the circulating water is 51 times greater than the heat exchange surface of the condenser tube, which contains this volume of coolant. The estimated adhesion probability of supersaturated carbonate salts on the crystallization centers in the circulation water flow is 0,981, and on the heat exchange surface of the condenser tube is 0,019.

thus, for determination of Fe effective value to estimate the required quality of makeup water at the design stage of industrial RCWS and water chemistry development, it is needed to determine the rate of calcium carbonate deposition on the sample surfaces in addition to controlling  $\chi$  and pH values in the circulating water [2].

When setting the pre-estimated Fe value for RCWS with evaporative cooling towers, changes in  $\chi$  values are lagging in comparison with changes in pH values. The worse is the quality of RCWS makeup water conditioning, the bigger is this lag.

### 3.3 Study on the Deposition Rate on Heat Exchanger Surfaces

Fig. 9 shows the research results of the deposition and corrosion rates  $J$  when the circulating water ( $\text{Fe} \approx 1,6$ ) flows over St. 20 steel samples under non-isothermal conditions with no dosage of inhibitors. Water samples were taken from the Siverskyi Donets River. The circulating water velocity was 1,0 m/s. The circulating water temperature was 22°C.



**Fig. 9** The research results of deposition and corrosion rates for St. 20 samples under non-isothermal conditions with no inhibitor treatment. 1– deposition rate; 2 – corrosion rate;  $J$  – corrosion rate,  $\text{mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ;  $t$  – time,  $\text{h}$ .

The obtained test data showed that under non-isothermal conditions the deposition rate of sparingly soluble salts on test samples washed with the circulating water, which has the same salt concentration, the same velocity, and preset temperature, will differ significantly after 80 h of testing. The amount of deposits on the test bench samples with direct heat supply (STHM) corresponded to  $J = 3,5 \text{ mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ . It was established that deposition rate reached stable

values after 600 h of circulation. These indicators are several times higher than standard allowable indicators for RCWS [1, 2]. This shows that deposition rate on the test sample surface depends on the corrosion resistance of the sample metal. Based on the above, in order to determine Fe effective value and select corrosion and scale inhibitors for the heat exchange surfaces of condensers using water of different class, it is needed to conduct preliminary tests on the scaled RCWS models for at least 480...600 h.

It has been established that deposition rate studies conducted at the production field with using the test bench (please see Fig. 1) allow us to determine the beginning of deposit formation after 240...250 h of RCWS continuous operation, as well as the dynamics of changes in the amount of deposits during the whole operation life of RCWS equipment. The deposition rate monitoring data correlate with the results of physical and chemical control of the working fluid properties (pH,  $\chi$  measurements, etc.). These indicators should be stable within a period of more than 480-600 h.

A smaller time period between the established  $\chi$  and pH stable mode determines the makeup water quality requirements for allowable deposits of maximum 0,05 mm per campaign.

### 3.4 Improvements of GCh technique for control of oil products in water

GCh methodology for control of turbine oil in water was improved with enhanced mathematical model of mass-exchange processes related to liquid extraction of turbine oil by a liquid extractant from the analyzed water sample [29]. The concentration  $C_i$  of turbine oil in water is determined by the formula:

$$C_i = \frac{C_0 \cdot V_e \cdot S_1}{V_w (S_2 - S_1)}, \quad (7)$$



where  $C_i$  is concentration of turbine oil in water, mg/dm<sup>3</sup>;  $C_0$  is the concentration of turbine oil in the liquid extractant added to the analyzed water sample, mg/dm<sup>3</sup>;  $V_e$  is extractant volume, cm<sup>3</sup>;  $V_w$  is volume of analyzed water, cm<sup>3</sup>;  $S_2$  is the chromatographic peak area corresponding to the concentration of turbine oil in the liquid extract after liquid extraction from the analyzed water sample with adding a specified amount of turbine oil to this extractant,  $mV \cdot s$ ;  $S_1$  is the chromatographic peak area corresponding to the concentration of turbine oil in the liquid extract after liquid extraction from the analyzed water sample with using a clean extractant,  $mV \cdot s$

The ranges of measured concentrations  $C_i$  of turbine oil in water samples and GCh measurement error characteristics are determined in accordance with [25] and are shown in Table 1.

**Table 1.** Error characteristics of GCh measurement data

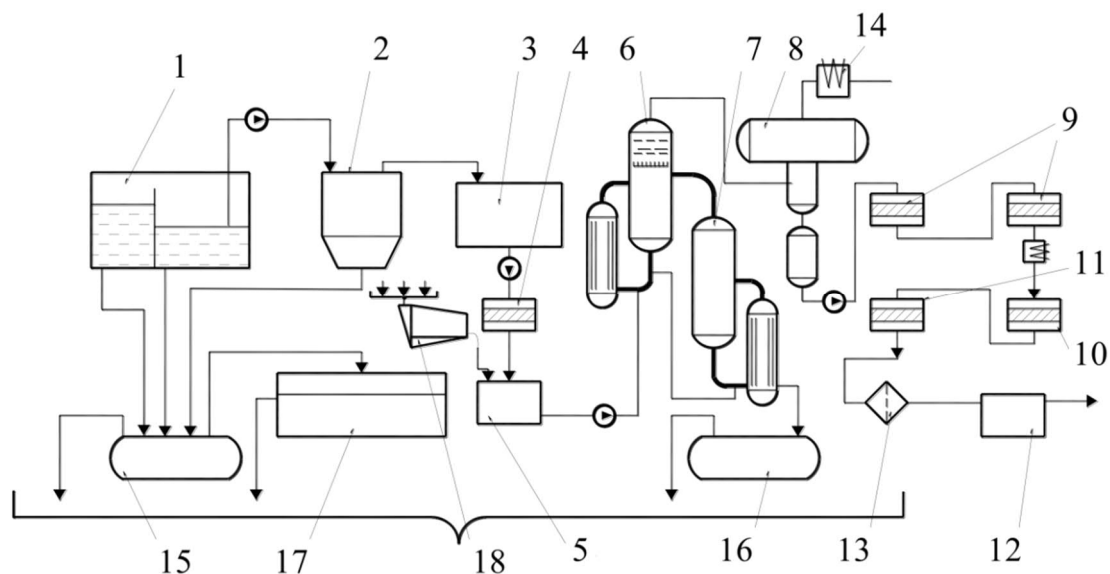
Turbine oil concentration measurement range, mg/dm <sup>3</sup>	$\pm\delta$ , % relative	$\sigma$ , % relative
From 0,02 to 0,5 inclusive	50	25
More than 0,5	25	13

**Notes:**  $\delta$  – relative error of GCh measurement data at  $P=0.95$ , % relative;  $\sigma$  – reproducibility relative standard deviation, % relative.

It follows from Table 1 that relative error of GCh measurement data  $\delta$ , % relative, and reproducibility relative standard deviation  $\sigma$ , % relative, decrease when turbine oil concentration in water increases.

### 3.5 Improved process flow diagram for floor drain radioactive water treatment

The improved process flow diagram for Khmelnitsky NPP floor drain radioactive water treatment is shown in Fig. 10.



**Fig. 10** Improved process flow diagram for Khmelnitsky NPP floor drain radioactive water treatment: 1 – floor drain sump tank; 2 – settling tank; 3 – decanting tank (clarified water); 4 – mechanical filter; 5 – tank for clarified floor drains; 6 – evaporator; 7 – residual evaporator; 8 – condenser and degasser unit; 9 – mechanical and adsorption filters; 10 – cation exchange filter; 11 – anion exchange filter; 12 – resin trap; 13 – monitoring tank; 14 – dephlegmator; 15, 16 – receiver tanks; 17 – radioactive sludge and used resin storage tank; 18 – centrifugal separator; 19 – direct-flow water electrical heater.

The operation of main components in the improved process flow diagram for

Khmelnitsky NPP floor drains radioactive water treatment is described in [1]. The

difference of the improved process flow diagram is the presence of direct-flow water electrical heater (item 19), which heats the clarified floor drain water before it enters the evaporator (item 6). This reduces the amount of aqueous vapor supplied to the evaporator (item 6), and accumulation of aqueous vapor condensate.

In our opinion, it is possible to use centrifuges, filter presses and screw dehydrators with pre-coagulation to increase the efficiency of radioactive water treatment from dispersed particles.

### ***3.6 Improvements in the method of discrete control over RCWS operational efficiency with automatic monitoring of THR and WCR indicators, deposition and corrosion rates to determine WCR efficiency by laboratory research and industrial tests of waters with different salt concentrations***

1. As per regulatory document [18], I&C equipment is used to measure the following indicators in NPP waters: acid conductivity (for H-cationized sample); conductivity; hydrogen index, pH; mass concentration of oxygen; mass concentration of chloride ions; mass concentration of sulfate ions; mass concentration of total organic carbon; mass concentration of iron; mass concentration of sodium ions; mass concentration of hydrazine (morpholine; ethanolamine); mass concentration of oil products; mass concentration of silicic acid; mass concentration of copper. For: a) automatic mode measurements: mass concentration of oxygen; mass concentration of sodium ions; conductivity; hydrogen index, pH; mass concentration of chloride ions; b) laboratory chemical analyses: mass concentration of copper; mass concentration of iron; mass concentration of ammonia; hydrogen index, pH; mass concentration of

hydrazine (morpholine; ethanolamine); mass concentration of oxygen; mass concentration of oil products; acid conductivity (for H-cationized sample); mass concentration of sulfate ions; mass concentration of sodium ions; mass concentration of chloride ions; mass concentration of boric acid; mass concentration of silicic acid; mass concentration of acetates and formates; mass concentration of total organic carbon;

2. Based on the obtained results of using the improved method for discrete control over RCWS operational efficiency with monitoring of THR and WCR indicators, as well as deposition and corrosion rates on internal heat exchange surfaces, we can recommend the following:

– for laboratory conditions: periodically measure J indicator (corrosion rate) using the corresponding metal samples, recirculating water solutions with a preset value of total salt concentration and using a scaled thermal hydraulic physical model for the specific RCWS type. Also, in automatic mode: in addition, perform continuous and simultaneous measurements of pH and  $\chi$  values in the recirculating cooling water; recirculating water temperatures at the cooling tower inlet and outlet; air temperatures and humidity at the cooling tower inlet and outlet;

– for laboratory conditions: periodically measure the content of oil products in recirculating cooling water and in floor drain radioactive water using the GCh method;

– the obtained measured data should be entered into the database for the further comparative analysis, and for determining the water chemistry efficiency in the laboratory studies and industrial tests for cooling waters with different salt concentrations used for

RCWS equipment operation, and for ensuring the reliable operation of NPP units.

#### 4. Conclusions

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To achieve the set goal, the following tasks were solved:

1. When the analysis considered main factors affecting the efficient and reliable operation of heat exchangers and up-to-date scientific and technical approaches to the study of existing RCWS water chemistry to prevent deposition of sparingly soluble salts and corrosion of power equipment, it was established that such major factors are: circulating water evaporation limits, pH,  $\chi$ , Ht (total hardness), At (total alkali), pHt values, total salt concentration in water, the dose of various scale and corrosion inhibitors, which control the growth of corrosion and deposition of carbonate salts and corrosion products on heat exchange surfaces of power equipment, the material of internal heat exchange surfaces, air humidity and temperature in RCWS cooling towers. This allows us to develop a scaled thermal hydraulic physical model for the specific RCWS type to study its efficiency.

2. The conducted THR study in the laboratory simulation of RCWS water chemistry established that during a relatively short time (160 h) the air temperature in RCWS cooling tower predictably changes by 5...15°C. With longer periods of time, the temperature will possibly change by several tens of degrees; After long-term THR studies of RCWS I and II circuit waters with different salt concentrations evaporated to different Fe values (Fe = 3,5...4,0 for RCWS I and Fe = 6,5...7,0 for RCWS II), no temperature difference changes were recorded at the heat exchanger inlets and outlets due to thermal

resistance effects of the formed deposits on the surface of metal test samples; The use of pH and  $\chi$  values in circulating water allows us to compare physical and chemical indicators of the circulating water quality throughout the entire period of researches by analyzing automatic chemical monitoring databases during the whole research; The pH value is stabilized after 50 hours of circulation, and ionic quasi-stability for other ions is achieved after 80 hours of circulation with consideration of  $Cl/Cl_m$  value. With stabilization of carbonic acid equilibrium in circulating water, the  $\chi$  indicator stabilizes with a slight delay after stabilization of pH value, which is characterized by the sum of  $CO_3^{2-} + HCO_3^-$  ions. This delay period corresponds to the quality of limed water, which has not been stabilized on clarifying filters ( $\Delta\chi = 50...80 \mu S \cdot cm^{-1}$ );  $\Delta\chi$  (6) can be used to estimate  $CaCO_3$  crystallization rate from circulating water; For determination of Fe effective value to estimate the required quality of makeup water at the design stage of industrial RCWS and water chemistry development, it is needed to determine the rate of calcium carbonate deposition on the surfaces of samples in addition to controlling  $\chi$  and pH values in the circulating water; When setting the pre-estimated Fe value for RCWS with evaporative cooling towers, changes in  $\chi$  values are lagging in comparison with changes in pH values. The worse is the quality of RCWS makeup water conditioning, the bigger is this lag. This allows you to control the RCWS operational efficiency.

It has been established that deposition rate studies conducted at the production field with using the STHM test bench allow us to determine the beginning of deposit formation after 240...250 h of RCWS continuous operation, as well as the dynamics of changes

in the amount of deposits during the whole operation life of the RCWS equipment. The deposition rate monitoring data correlate with the results of physical and chemical control of the working fluid properties (pH,  $\chi$  measurements, etc.). These indicators should be stable within a period of more than 480-600 h. A smaller time period between the established  $\chi$  and pH stable mode determines the makeup water quality requirements for allowable deposits of maximum 0,05 mm per campaign. This allows using test methods to study RCWS efficiency with application of different scale and corrosion inhibitors for internal heat exchange surfaces of power equipment.

4. When improving the GCh technique for control of oil product (turbine oil) in water, the procedures for standard adding turbine oil solution in liquid extractant - n-hexane were used. It allows us to determine the content of turbine oil in water with the concentration ranging from 0,02 to 100 mg/dm<sup>3</sup> with the reproducibility relative standard deviation not more than 25% relative.

5. The direct-flow water electrical heater, which heats the clarified floor drain water before it enters the evaporator, was added to the improved process flow diagram for Khmelnitsky NPP floor drain radioactive water. This reduces the amount of aqueous vapor supplied to the evaporator and accumulation of aqueous vapor condensate.

6. When improving the method for discrete control over RCWS operational efficiency with automatic monitoring of THR and WCR indicators, as well as deposition and corrosion rates to determine WCR efficiency by laboratory research and industrial tests of waters with different salt concentrations, the following has been

established. For laboratory conditions, it has been recommended to periodically measure J (corrosion rate) value using the related metal samples, recirculating water solutions with a preset value of total salt concentration and using a scaled thermal hydraulic physical model for the specific RCWS type. For automatic mode, it has been recommended to additionally perform continuous and simultaneous measurements of pH and  $\chi$  values in the recirculating cooling water; recirculating water temperatures at the cooling tower inlet and outlet; air temperatures and humidity at the cooling tower inlet and outlet. This allows you to control the RCWS operational efficiency.

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# ІНТЕГРАЛЬНІ МЕТОДИ КОНТРОЛЮ СКЛАДНИХ ТЕХНОЛОГІЧНИХ ПРОЦЕСІВ В ОХОЛОДЖУЮЧИХ СИСТЕМАХ АЕС

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*Актуальність дослідження полягає у забезпеченні надійності експлуатації оборотних систем охолодження (ОСО) обладнання АЕС та вибір методу кондиціювання скидних вод. Мета роботи: науково-технічне обґрунтування умов ефективного забезпечення та підвищення надійності і ефективності довгострокової експлуатації обладнання ОСО АЕС. У процесі роботи виконано аналіз основних факторів, що впливають на ефективну і надійну роботу теплообмінників, і сучасних науково-технічних підходів до дослідження водно-хімічних режимів (ВХР) діючих схем ОСО для попередження відкладень важкорозчинних солей і корозії металів енергетичного обладнання; дослідження тепло-гідравлічних режимів (ТГР) лабораторного моделювання ВХР ОСО; дослідження інтенсивності відкладень на теплообмінних поверхнях (ТОП); удосконалення: методики хроматографічного контролю вмісту домішок нафтопродуктів у воді; принципової технологічної схеми очищення радіоактивних трапних вод; методів дискретного контролю за ефективністю експлуатації ОСО при моніторингу показників ТГР і ВХР і величин інтенсивності відкладень під час лабораторних досліджень і промислових випробувань. Отримані результати дозволяють виконати науково-технічне обґрунтування умов ефективного впровадження структурного перемикачів блоків для підвищення коефіцієнту використання встановленої потужності (КВВП) і економічного використання води при несенні окремими енергетичними блоками крупних енергетичних об'єктів змінного навантаження з урахуванням встановленої потужності, термінів експлуатації і стану теплообмінного обладнання за рахунок застосування відокремлених ТГР і ВХР ОСО із встановленими індивідуальним нормами кількості продувної води та її можливості повторного застосування в якості додаткової води для енергетичних блоків.*

**Ключові слова:** вода, масло, методи контролю, охолодження, хроматографія