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WATER PURIFICATION IN INNOVATIVE ECOSYSTEMS. (Integrative inventions for the purification of process water with the aim of its recirculation)

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Abstract

The article examines the development and implementation of integrative technological solutions for the treatment, purification, and regeneration of contaminated process water with the aim of its recirculation. It describes a scalable, modular, and adaptive system based on synchronized electrochemical and hydrodynamic processes that enable effective removal of organic and inorganic impurities, including metals, sulfates, phosphates, oils, and other contaminants. Particular attention is given to the design of an electrochemical reactor with parallel electrode cells and a synchronized power supply system, ensuring stable operation under fluctuating conditions. The study highlights the role of coagulation, sedimentation, and redox reactions in forming removable impurity complexes, as well as the importance of automated control systems with feedback for process stabilization. The proposed solution is characterized by low energy consumption, high efficiency, and adaptability to varying conditions, including low-conductivity water. Its modular design enables integration into larger systems and supports autonomous operation.

The article also outlines structural and technological features that enhance performance, such as synchronized current supply and optimized flow conditions, demonstrating improved treatment efficiency and environmentally sustainable water treatment for industrial and wastewater applications.

Keywords: *Water; Organic impurities; Inorganic impurities; Impurity complexes; Automated water treatment module; Environmentally friendly production; Automatic process control and feedback; Computerized module; Coagulation; Sedimentation; Electrodes; Power supply units; Energy delivery mechanism; Power supply units; Synchronously connected power supply units*

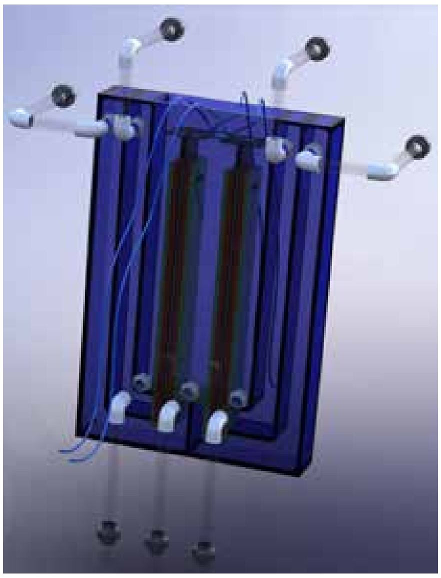
Introduction:

In recent years, with the emergence of so-called smart technologies across many industries, along with their corresponding smart components, conditions have arisen in various application areas for the development of integrative patents. These patents combine features and distinctions of devices (apparatuses), complex systems (supersystems and their constituent subsystems), software, and associated methods.

This direction has developed particularly intensively with the incorporation of artificial intelligence elements and artificial neural networks into control and monitoring systems.

In turn, the advancement of core technologies as part of the ecosystem and infrastructure of smart manufacturing environments requires the systematic development of production and infrastructure modules – primarily comprehensive process water treatment systems that operate without chemical reagents and are based on electrochemical reactors performing treatment in an upward flow of the processed liquid.

Figure 1. *Electrochemical reactor with two electrochemical cells*



Brief product description

Proprietary integrated, scalable, adaptive, and modular systems and equipment, as well as technical support services for the treatment/purification/regeneration of commercial types and volumes of contaminated flowing water.

They are based on the separation and removal of inorganic and/or organic impurities (such as metals, sulfates, phosphates, oils, and lubricants) from contaminated water flowing through and interacting with electrodes placed in at least two electrode cells, specifically designed and constructed to ensure a stable and synchronized electrochemical process and hydrodynamic flow conditions.

An efficient and cost-effective design and operation of the energy supply mechanism, including a pair of synchronously connected and operating power supply units, provide synchronized power delivery to the electrodes, which oxidize and reduce components in the contacting flowing water.

The formed oxidized/reduced components of the water create complex impurities in the flowing water through mechanisms including coagulation and sedimentation, thereby forming impurity complexes that are removed, for example, by sedimentation, from the flowing water.

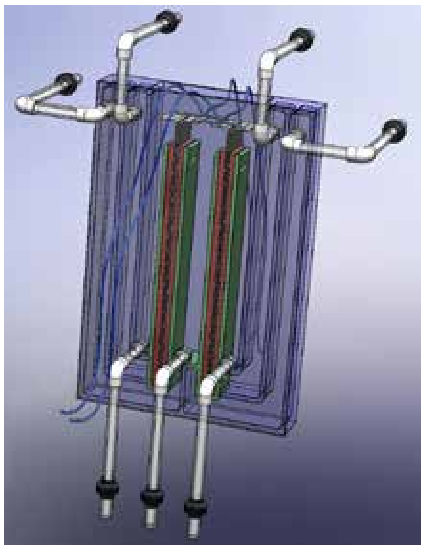
The system is automated and computerized, including equipment, procedures, and software for automatic process control and feedback.

Part 1 – General introduction and overview

The following provides a general introduction and overview of the water treatment/purification/regeneration system.

The invention relates to the general field of water treatment/purification/regeneration, and more specifically to a method, device, and system for the treatment/purification/regeneration of commercial types and volumes of contaminated flowing water.

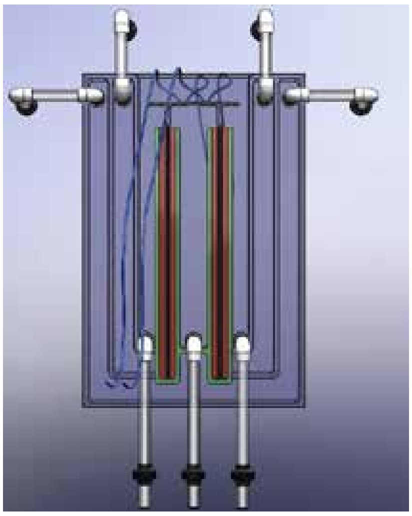
Figure 2. *Internal structure of the electrochemical reactor housing with two parallel electrochemical cells*



The invention is characterized by a set of synchronized and synergistically interconnected electrochemical and hydrodynamic properties, characteristics, behaviors, and phenomena that are novel (unanticipated) and inventive (not obvious from) prior art in the field of water treatment/purification/regeneration.

The structure and operation of the invention and its components are designed, constructed, and implemented using conventional engineering methods, equipment, and materials, based on well-established physical, chemical, and related mathematical theories, laws, and principles.

Figure 3. *Electrochemical reactor with upward-flow water treatment*



The invention corresponds to a new and unique synchronized and synergistic model of a nonlinear system influenced by continuously occurring fluctuations in key system parameters associated with the treated flowing water, namely the concentration of chemical components and the electrical conductivity of the water.

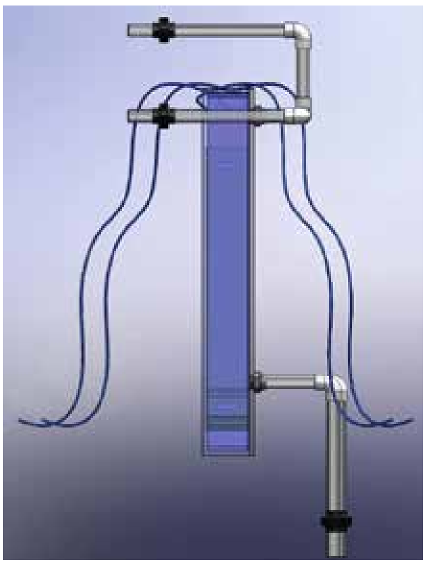
Since the invention for treating contaminated flowing water must operate under fluctuating conditions, it therefore includes provisions for mitigating "selective instabilities" characteristic of most environmental technologies. This is achieved through mechanisms of an "organic" or "natural" nature, which, as part of the described invention for water regeneration, enable synchronization and synergistic interconnection of electrochemical and hydrodynamic properties, characteristics, behaviors, and phenomena.

An important objective of the invention is based on comprehensive and well-founded principles of synchronization and synergy applicable to the technology of complex treatment of contaminated flowing water.

The invention addresses the task of creating an efficient, mobile, adaptive, and self-sufficient device (an electrochemical and hydrodynamically stable reactor) as part of a larger overall system for the regeneration of contaminated flowing water.

The effectiveness of the proposed technical solution is ensured by:
- low levels of energy consumption required for the process;
- low levels of non-productive energy losses within the process cycle;
- the possibility of combining and synchronizing certain energy-intensive autonomous technological tasks, such as electrolytic dissolution of the anode (electrolytically coagulating element) and the simultaneous formation of regions with highly concentrated oxidizing agents;
- reduction of process duration through precise synchronization of cycle timing with the interaction of technological stages;
- stabilization and synchronization of process rates, concentrations, energy consumption, and time factors;
- a high level of reproducibility and technical standardization of the process.

Figure 4. *Electrode proportions of the electrochemical reactor*



The mobility of the proposed solution is ensured by the following:

- a minimized design;
- a modular structure with full synchronization of modules;
- a flexible interaction scheme between modules, with the possibility of synchronized switching of additional treatment stages, allowing operation during transitional periods.

The proposed technical solution is adaptable due to:

- synchronous automatic adjustment of process power supply parameters in response to changes in operating conditions and initial characteristics, such as variations in water conductivity;
- a modular, autonomous system consisting of identical energy-converting and generating units operating synchronously to supply power to the process;
- a feedback sensor system providing signals used to stabilize and synchronize process parameters.

The autonomy of the proposed solution is ensured by:

- a complete cycle of technological operations and transitions synchronized across all parameters, providing the required final regulation;
- a fully autonomous system capable of treating various types and volumes of contaminated flowing water sources;
- synchronized integration of different treatment/purification/regeneration operations to achieve optimal results;
- extraction of conventional outcomes from the process, such as pH adjustment.

The main advantages of the invention for the treatment/purification/regeneration of contaminated flowing water are based on the implementation of fundamental characteristics of the invention and the following structural and technological achievements:

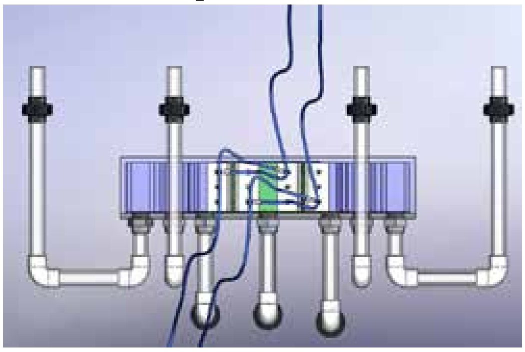
- effective stimulation of co-sedimentation (multi-sedimentation) in the presence of metals and other materials in contaminated water, enabling their precipitation under fundamentally different conditions;
- effective stimulation of co-sedimentation without significant changes in water acidity or alkalinity;
- simultaneous implementation of hydroxidation and electrocoagulation without additional energy or time costs;
- efficient treatment of contaminated flowing water sources within short timeframes, enabling acceleration of automated production lines;
- acquisition of indirect data on changes in easily measurable system parameters during treatment, using feedback to assess the quality of treated/regenerated water;
- acceleration of automated control systems;
- enhanced performance of flexible automated technological modules and complexes;
- adaptability to treatment of very low-conductivity water (e.g., 1–5 μS);
- achievement of a twofold increase in electrical current or voltage parameters without additional energy consumption, by adjusting one parameter without changing the other;
- remote control of the system, including monitoring of process parameters and elimination of imbalances between electrochemical and hydrodynamic conditions;
- autonomous local shutdown and remote control without reprocessing already treated water, enabling closed-loop recirculation;
- rapid adjustment of operating modes, with automatic synchronization of DC power sources and the hydrodynamic system under varying configurations and interaction modes;
- integration of the invention into larger systems and processes, such as reverse osmosis and ultrafiltration systems.

Additional advantages provided by advanced characteristics of system components include:

- the presence of at least two synchronously operating DC power sources;
- series connection with voltage doubling relative to that required for a given conductivity, resulting in increased concentrations of oxidizing and reduc-

ing agents and a higher proportion of hydroxides in the treated water;
– parallel connection with current doubling, leading to higher concentrations of oxidants and reductants and improved precipitation quality;
– enhanced coagulation in high-current mode (up to approximately A/dm²), enabling dissolution of aluminum electrodes and achieving reaction rates approximately twice those of conventional electrocoagulation (typically 1–2 A/dm²);
– capability for electrolytic recovery of precious metals during hydrodynamic stabilization as water passes between electrodes;
– applicability for seawater treatment;
– real-time monitoring capability with automatic fault detection, recovery of synchronized operation, and notification of system status;
– maintenance of output water quality with reduced power consumption compared to a single high-power source;
– presence of common cathode and anode sections within interelectrode spaces;
– higher electric field intensity in interelectrode regions;
– reduced hydraulic resistance to water flow;
– increased concentration of generated oxidizing and reducing agents;
– prevention of salt shedding from the cathode;
– avoidance of anode scale accumulation;
– improved usability of system characteristics;
– extended electrode service life.

Figure 5. *Electrochemical reactor – plan view*



Part 2 – Structure, function, and operation

The following provides a detailed and illustrative description of the structure, function, and operation of the main and alternative embodiments, as well as their components, of the water treatment/purification/regeneration system.

Heterocoagulation:

The installation of electrode cells with aluminum or pure iron anodes in the electrochemical reactor for water treatment/purification/regeneration produces an effect in which the primary process of generating oxidizing and reducing agents in the water flow is supplemented by anodic by-products that act as coagulants. This facilitates the process associated with the required separation of substances in the dispersed phase from the dispersion medium.

This "coagulation threshold" increases relatively rapidly. In most cases, the flowing contaminated water contains various salts of multivalent metals, which hydrolyze to form colloidal hydroxides. This stimulates the process of heterocoagulation and often the primary coagulation process as well.

In heterocoagulation, different dispersed systems mutually coagulate, resulting in particles of one dispersed phase adhering to particles of another phase. Heterocoagulation is enhanced by the mutual mixing of segregated salts with differently charged particle surfaces, since ionic electrostatic forces between them lead to attraction rather than repulsion.

The kinetics of Brownian motion in the coagulation of colloidal systems determine the required contact time of the flowing water interacting with the electrodes and the flow through the cells in the interelectrode space, such that the number of independent, unbound units is reduced by half, leading to the establishment of a "coagulation threshold" in contact time.

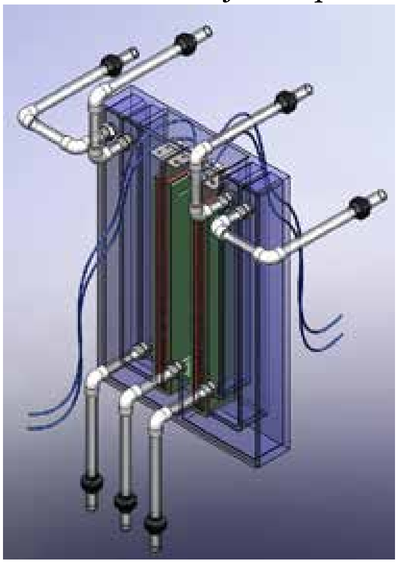
In the absence of an energy barrier, that is, at high current densities (for this invention approximately 4 A/dm²), a = 1; in the presence of an energy barrier, a < 1.

The residence time of the electrode cell in the interelectrode space in a system with a throughput of 1 m³/hour is approximately

3 seconds. During this time, the entire volume of water passing through the electrode cell is subjected to the action of a spatial coagulating network.

For a water sample passing through the electrode cell approximately 0.2–0.6 seconds after leaving the interelectrode space, both from the anode and the cathode, the bulk density of the sample characterizes the initial turbidity, that is, the segregated dispersed medium (sediment).

Figure 6. *Electrochemical reactor housing with two parallel electrochemical cells, with water directed in a uniform upward flow*



The unstructured sediment phase formed within approximately 1–2 minutes transitions into a structured sediment phase and a consolidated sludge layer.

A candelabra-shaped (specifically, menorah-like) labyrinth configuration or form of the electrochemical reactor used in the W2W system provides a synchronized, electrochemically active and hydrodynamically stable environment for separating impurities from the flowing water.

To achieve optimal hydrodynamic synchronization of all parallel flows, the housing of the electrochemical reactor is filled with a labyrinth in the shape of a "menorah."

This design allows for:

– placement of the electrochemical reactor in both horizontal and vertical orientations;
– stabilization of dynamic flow without additional energy consumption;
– synchronization of all incoming flows for each electrode cell;
– synchronization of parallel flow movement within the interelectrode space.

The movement and synchronization of contaminated water flows are schematically shown in Fig. 1, while the menorah-shaped labyrinth is shown in Fig. 2. The flowing water is divided into two equal parallel streams, driven by pressure in the range of approximately 1.2 to 1.5 bar.

As shown in the electrochemical reactor, the channels are equipped with openings directed toward the working chamber, while other openings are also oriented toward the working chamber. The primary and secondary working chambers are connected to adjacent channels, respectively. The channels of the two working chambers are interconnected by an opening. Since the operation of the chambers is identical, i.e., synchronized, hydrodynamic equilibrium can be considered for only one of them. The flow in one channel exits through an opening into an adjacent channel and reaches the working chamber.

Main structural characteristics of the electrochemical reactor:

– a labyrinth housing design in the form of a "menorah";
– hydraulic connection between adjacent channels of the labyrinth;
– geometric and hydraulic symmetry between homogeneous elements of the reactor housing;
– presence of two electrode cells within the housing, identical in all structural and technological parameters;
– trapezoidal cross-section of electrode cells (in the case of flat-parallel electrodes, as an option) with parallel active working surfaces;
– self-sealing design of electrode cells;
– composite reactor housing;
– alternative spatial orientations of the housing;
– alternative electrode cross-sectional shapes;
– coaxial tubular electrodes (optional);
– two independent, identical DC power sources synchronized in all main parameters;

— symmetrical (optional) or asymmetrical (optional) positioning of active electrode surfaces;
– various configurations of interelectrode cross-sectional geometry;
– combined cathode and anode spaces within the interelectrode volume (optional);
– interconnected zones linked by adjacent symmetrical channels within the labyrinth;
– empirical relationship between the area of interconnected zones and the interelectrode cross-sectional area.

Empirical parameters:

The interelectrode space area is approximately 600 mm². The width of the active electrode surface is about 100 mm. The electrode cross-sectional area is approximately 200 mm². Preferred electrode materials include stainless steel, titanium, aluminum, iron, or carbon–carbon composites.

Main technological characteristics of the electrochemical reactor:

– stabilization and uniform distribution of water flow at the reactor inlet;
– gravitational stabilization and synchronization of flows entering the interelectrode space;
– synchronous passage of water streams through the interelectrode space within intersecting magnetic field lines under high voltage between active electrode surfaces;
– current supply from two synchronized, equivalent DC power sources, with doubling of either current or voltage through series or parallel synchronization combined with hydrodynamic stabilization;
– simultaneous parallel operation of oxidant/reductant generation and electrochemically controlled dissolution (coagulant ion saturation) using a single energy supply mechanism;
– separate discharge of catholyte and anolyte (optional);
– sediment accumulation in settling tanks using hydrophobic enhancers and sedimentation elements, including sedimentation fibers, to increase settling rates over time.

Additional description of system operation:

The system for water treatment/purification/regeneration is applicable to both industrial and wastewater streams. The treated/regenerated water meets quality requirements for reuse in technological cycles.

Water treatment is carried out using an electrochemical method in which constant voltage is applied to adjacent electrodes, resulting in the formation of alkaline substances (at the anode) and acidic substances (at the cathode). Since water contains various contaminants and impurities, they react chemically with the electrochemically generated alkaline and acidic components.

The chemical reactions occurring in the flowing water near the electrodes are redox reactions. Thus, electrolysis consists of reduction at the cathode and oxidation at the anode.

The metal anode may be either (a) insoluble, serving only as a site for electron transfer during electrolysis, or (b) soluble (active), undergoing oxidation during the process.

The redox activity of the electric current often enhances oxidation and reduction reactions.

Analysis of standard electrode potentials shows that metal cations such as Cu^{2+}, Hg^{2+}, Ag^{+}, Pt^{2+}, and Pt^{4+}, which have standard electrode potentials higher than hydrogen, are fully reduced during electrolysis, depositing either on or near the cathode.

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