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INTEGRATED COMPREHENSIVE WATER TREATMENT MODULE AT THE WATER SUPPLY SYSTEM INLET (Electrochemical treatment of industrial wastewater for the removal of heavy metal ions and enabling the repeated reuse of treated water in an autonomous recirculation mode, including in autonomous water treatment systems within the infrastructure of a smart mobile home and its structural equivalents)

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Abstract

The article examines an electrochemical technology for the treatment of industrial wastewater aimed at removing heavy metal ions and enabling the repeated reuse of treated water in autonomous recirculation systems. The study reviews major sources of heavy metal contamination and evaluates existing treatment methods, demonstrating that conventional approaches do not fully address the challenges of water regeneration and reuse. An integrative water treatment module is proposed, combining multifunctional electrochemical reactors, aeration and sedimentation units, ion-exchange columns, automatic filtration systems, and intelligent non-contact water quality monitoring based on electromagnetic resonance spectroscopy. The technology offers reduced dependence on chemical reagents, minimal toxic waste generation, high operational flexibility, advanced automation, and cost-effective water regeneration. The study concludes that the integration of electrochemical, ion-exchange, and digital control technologies provides a promising foundation for sustainable and resource-efficient next-generation water treatment systems.

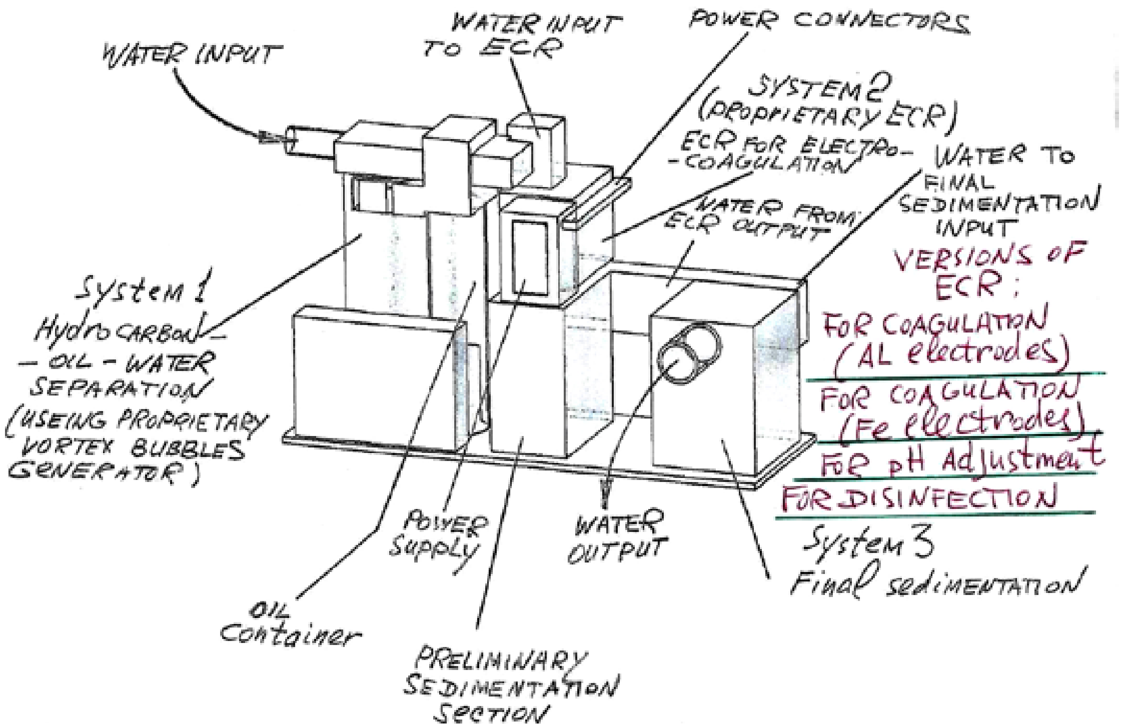
Keywords: *Water treatment; Water treatment at the water supply system inlet; Water treatment module; Comprehensive water treatment module; Electrochemical treatment of industrial wastewater for the removal of heavy metal ions and enabling the repeated reuse of treated water in an autonomous recirculation mode; Autonomous water treatment systems within the infrastructure of a smart mobile home and its structural equivalents; Technologies used in smart mobile home infrastructures capable of providing effective treatment of all types and classes of wastewater, including water that does not contain metals*

Approximately 16 different technological methods for the treatment of metal-containing wastewater are currently known.

The most widely used method is chemical reagent treatment. Under this method, caustic soda is added to the water, increasing its alkalinity to a level at which metal hydroxides begin to precipitate.

Methods of artificial coagulation and flocculation can generally be disregarded, as their economic performance is highly unfavorable due to their high cost.

Figure 1.



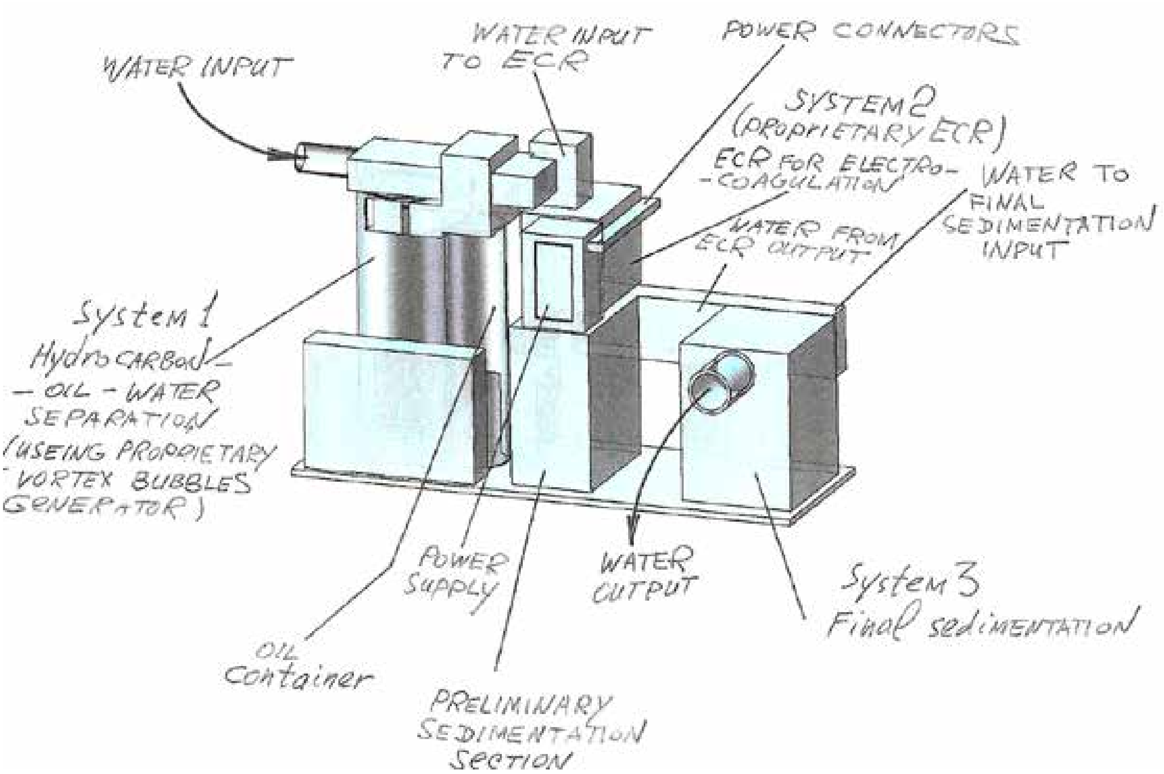
The electrocoagulation method can compete with the aforementioned chemical reagent method in terms of both cost and efficiency. In recent years, particularly in high-technology industries, this method has gained considerable popularity. However, it is unable to comprehensively solve all existing water treatment challenges. Moreover, the transition from a reagent-based treatment system to an electrocoagulation system requires significant capital investment while still failing to address all fundamental issues.

None of the currently known methods fully solve the problem of water treatment for repeated reuse and, consequently, the need to reduce water consumption for technological processes.

At present, electrocoagulation technologies represent the most advanced approaches for the treatment of metal-containing industrial wastewater. Despite their significant advantages over older chemical reagent methods, electrocoagulation technologies do not resolve all critical issues associated with water treatment processes and possess several substantial limitations that are addressed by the integrated water treatment technology developed for the infrastructure of a smart mobile home.

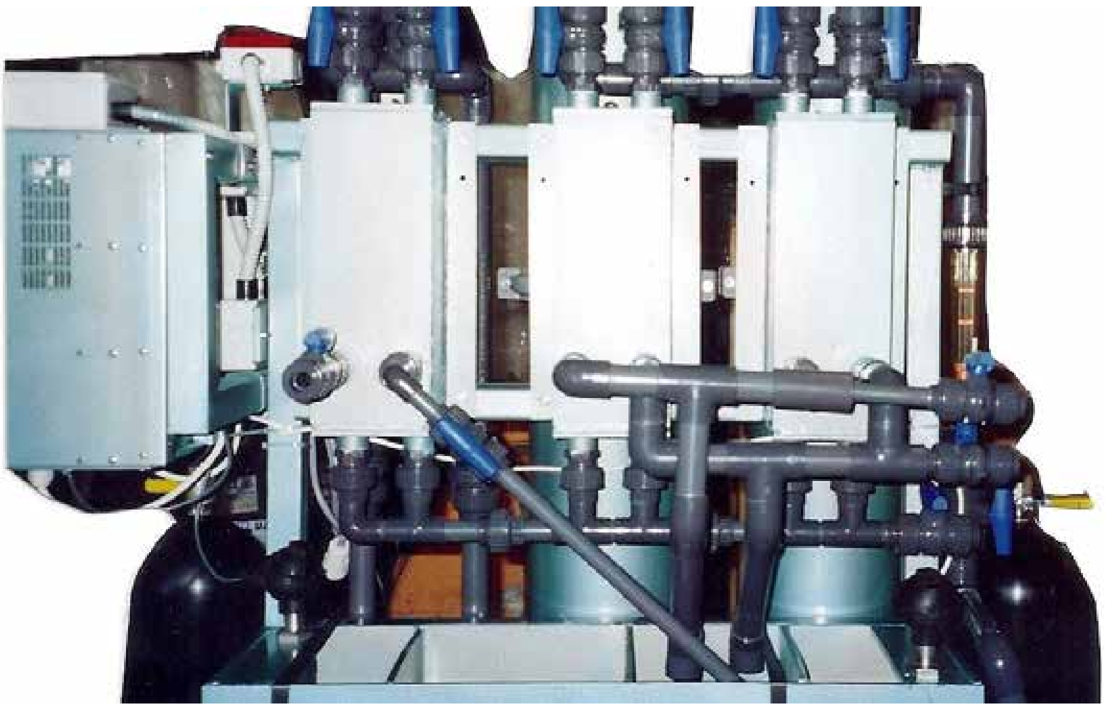
The fundamental advantages of the proposed technology include: the elimination of the need for sedimentation processes; the absence of toxic waste requiring complex and costly disposal methods; insensitivity of the treatment process to the acidity level of the water being processed and, consequently, the absence of any need for pH adjustment; the versatility of the electrochemical reactor modules, allowing inexpensive and straightforward modification and customization for specific customer requirements while preserving the core technological and design principles; the possibility of extensive standardization and unification of smart mobile home water treatment modules; the capability of integration into virtually any technological production line; the possibility of preliminary separation of electrically conductive and non-conductive components of aqueous solutions; and the possibility of using natural, including biological, ion-exchange materials alongside electrochemical metal extraction from water.

Figure 2.



The economic advantages of the water treatment technology developed for the infrastructure of a smart mobile home should also be considered separately.

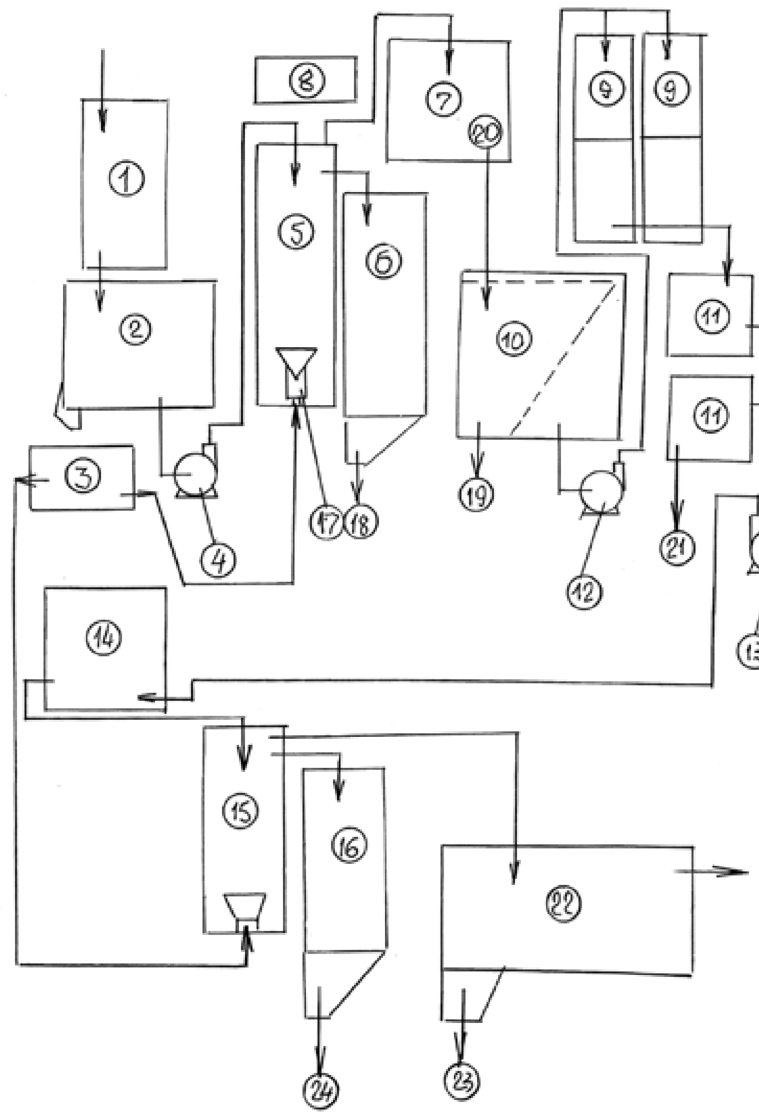
Figure 3.



The vast majority of technologies currently used in water treatment and purification processes rely on chemical reagents. The market niche for technologies that operate without chemical reagents is virtually unoccupied. An even less developed niche is that of treatment technologies that do not generate difficult-to-dispose-of waste products. At present, such technologies are practically absent from the market. The seven technological modules that form part of the smart mobile home water treatment infrastructure, together with their various modifications and configuration options, provide a basis for occupying market sectors related to comprehensive water purification, regeneration, and the repeated reuse of water resources.

As of today, no technologies have been identified that enable the regeneration and repeated reuse of industrial wastewater with minimal, economically acceptable costs while generating little to no toxic waste. Furthermore, the technical characteristics of the modules within the smart mobile home water treatment system allow them to be integrated into existing installations and production lines that utilize chemical and other treatment technologies. In such applications, the modules originating from the smart mobile home infrastructure solve specific local process challenges while simultaneously enhancing the overall technical performance of the existing systems due to their advanced technological capabilities. As a result, market entry for smart mobile home water treatment technologies within this category is significantly facilitated.

Figure 4.



Layout of operating modules within the integrative comprehensive water treatment module at the water supply system inlet.

The integrative comprehensive module is designed to treat groundwater and water resources of comparable quality to meet applicable water quality standards.

The capacity of the integrative comprehensive module ranges from 1,500 to 3,000 gallons per day.

The system consists of a series of sequential water monitoring and treatment units.

The treatment and monitoring process begins with a collection tank that receives all incoming water. Within this tank, comprehensive active monitoring of all key water quality parameters is performed using principles of electromagnetic resonance spectroscopy.

The water then enters a basin whose primary function is initial sedimentation and separation of the water stream into a fraction containing contaminants and sediment, and a fraction that has undergone gravitational sedimentation. The latter is pumped into a primary aeration column, where oxygen is dissolved into the water to the maximum possible extent through the action of an aerodynamic vortex foam generator connected to a compressor.

Upon completion of the first aeration and oxygen dissolution stage, a portion of the water containing foamed sediment is removed, while the remaining portion is directed to an electrochemical reactor operating under a multifunctional treatment cycle and equipped with electrochemical cells utilizing water-permeable carbon-carbon electrodes.

From the electrochemical reactor, the treated water is directed to a sedimentation basin, where it is divided into two streams. One stream is discharged for disposal after sediment separation, while the second, purified stream – processed through the combined multifunctional operating cycle of the reactor's electrochemical cells and the contact grid of the sedimentation basin – is directed to ion-exchange treatment columns.

Following treatment in the ion-exchange columns, the purified water is passed through automatic self-cleaning filters. After sediment removal within the filters, the water is directed to a second electrochemical reactor operating under a multifunctional treatment cycle. This reactor can be configured to perform several electrochemical water treatment operations without the use of chemical reagents. These operations include pH adjustment, disinfection, coagulation, flotation, and antibacterial treatment.

The water treated in this manner is then directed to aeration columns, where oxygen is forcibly dissolved until full saturation is achieved. At the outlet of these columns, sediment and other foamed contaminants are separated from the main water flow and disposed of, while the remaining purified water is directed through a storage reservoir for delivery to end users.

The diagram designates the following components:

1 – A tank into which water enters from the supply system or collection manifold. This tank contains active online monitoring systems for detecting contaminants in the water based on the principles of electromagnetic resonance spectroscopy (an invention of the project authors).

2 – A primary sedimentation basin connected to Pump 4 and equipped with a sludge discharge line.

3 – A compressor connected to aerodynamic foam generators installed in the columns for the separation of sediment fractions and other contaminants.

4 – A centrifugal pump with all necessary supporting infrastructure.

5 – A column for aeration and oxygen dissolution in water, as well as for lifting foamed contaminants and organic matter to the upper section of the column.

6 – A column for separating foamed sediment and contaminants from the water mass.

7 – An electrochemical reactor with a multifunctional operating cycle. The reactor can be configured for several electrochemical water treatment operations without the use of chemical reagents. These operations include pH adjustment, disinfection, coagulation, flotation, and antibacterial treatment.

8 – A non-contact water quality monitoring system controlled by a dedicated processor connected to sensor modules installed at designated sections of the pipeline network and operating on the principles of electromagnetic resonance spectroscopy.

9 – Sectional ion-exchange treatment columns. Depending on the required processing capacity, a column may contain one, two, or three sections. This structure allows a single column to incorporate up to three ion-exchange materials, including natural ion-exchange media such as zeolite.

10 – A sedimentation basin receiving the discharge from the electrochemical reactor. Water separated from sediment in this basin is pumped to the inlet of the ion-exchange treatment columns (9).

11 – Automatic self-cleaning mechanical filters, which may be replaced by automatic membrane filters.

12 – A pump supplying purified water from sedimentation basin 10 to the ion-exchange treatment columns 9.

13 – A pump supplying purified and filtered water from filters 11 to the second electrochemical reactor operating under a multifunctional treatment cycle.

14 – An electrochemical reactor with a multifunctional operating cycle. The reactor can be configured for several electrochemical water treatment operations without the use of chemical reagents. These operations include pH adjustment, disinfection, coagulation, flotation, and antibacterial treatment.

15 – A column for aeration and oxygen dissolution in water and for lifting foamed contaminants and organic matter to the upper section of the column. An aerodynamic vortex foam generator is installed in the lower section of the column.

16 – A column for separating foamed sediment and contaminants from the water mass.

17 – An innovative aerodynamic vortex foam generator, the inlet of which is connected to the compressor outlet.

18 – The outlet and discharge line from Column 6, which functions as a column for separating foamed sediment and contaminants from the water mass.

19 – A sludge discharge line for removing sediment from sedimentation basin 10.

20 – A pipeline conveying water treated in the electrochemical reactor to sedimentation basin 10. Water within the electrochemical reactor may undergo several treatment operations without the use of chemical reagents. These operations include pH adjustment, disinfection, coagulation, flotation, and antibacterial treatment.

21 – A backup sludge discharge line from the automatic mechanical filters or their equivalents – membrane filters.

22 – A final storage tank for treated water prior to distribution for consumption.

23 – A backup discharge line for removing accumulated sediment and contaminants from the storage tank.

24 – A discharge outlet from Column 16, which is used for separating foamed sediment and contaminants from the water mass.

In the described configuration, all incorporated modules are multifunctional and can be adjusted to operate with several types of source water supplied to the inlet of the integrative comprehensive treatment module.

For the control and management of the electrochemical reactors, the integrative comprehensive module incorporates a control and monitoring system functionally connected to non-contact electromagnetic resonance sensor modules operating on the principles of electromagnetic resonance spectroscopy.

The system is capable of operating in a fully autonomous automatic mode, providing complete control over treatment results and water quality at every stage of the treatment process.

The system offers complete operational flexibility and, during operation and configuration, can modify both the sequence and specific characteristics of the treatment process according to operational requirements and the technical parameters of the integrated components and subsystems.

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