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Concept of a Modular Water Treatment System for Autonomous and Industrial Facilities with Consideration of Integration into a Smart Mobile Home

Artem Aleksanian
Bachelor of Architecture, independent researcher, graduate of Yuri Gagarin State Technical University of Saratov, Russia

Abstract: The article presents a concept for a modular electrochemical system for the treatment, how far such a system can be integrated into a smart mobile home. The work is conceptual and design-oriented: no independent laboratory or industrial testing was carried out, and the quantitative characteristics cited are design assumptions. A seven-module architecture is proposed, comprising storage and equalization tanks, filtration and sorption modules, an aerodynamic turbo-flotation unit, an electrochemical reactor, an ion-exchange column, self-cleaning mechanical filters, and a monitoring and control unit. Five effluent groups are defined by metal ion content and mapped to specific module sequences, which constitutes the principal contribution regeneration and reuse of wastewater at off-grid residential facilities and industrial sites, together with an assessment of of the work. The proposed configuration is compared qualitatively with reagent-based treatment. Resonant impedance monitoring and machine learning are treated as development directions rather than implemented functions. A programme of experimental verification is set out, covering contaminant removal, specific energy consumption, electrode service life, waste generation and life-cycle cost.

Keywords: artificial intelligence, electrochemical water treatment, electromagnetic resonance spectroscopy, ion exchange, modular system, smart home, turbo-flotation, wastewater regeneration

1. Introduction

1.1. Relevance of the problem

Sensible handling of water today is less an environmental slogan than a practical engineering task. Fresh water consumption and discharge volumes can both be reduced if the effluent is treated, regenerated and fed back into a technical or utility cycle. In intelligent real estate facilities, water treatment ceases to be a stand-alone piece of equipment and becomes one of several interconnected engineering subsystems linked by automated monitoring and control [1, 17]. Industrial wastewater containing metal ions and other inorganic pollutants is generated during electroplating and coating operations, etching and degreasing of metal parts, in metallurgical and mining processes, and when process equipment and tanks are washed out [3, 5, 16].

Chemical, physicochemical, biological, sorption, membrane and electrochemical methods are all used for wastewater treatment, both individually and in combination [2, 5, 17]. Chemical precipitation is among the most widespread: alkaline reagents raise pH, dissolved metals convert into sparingly soluble compounds, and the sludge is separated [5, 17]. The method is proven but carries recurring costs, since reagents must be purchased and dosed and the sludge must be dewatered, hauled away and disposed of.

Electrocoagulation is arranged on a different principle. The coagulant is not dosed from a drum; it forms in the cell through electrode reactions, usually on iron or aluminium electrodes. Performance depends on electrode geometry and material, current density, pH, conductivity, flow rate and contact time [3, 4, 11-14]. Recent literature shows a clear shift towards combined schemes in which electrocoagulation is paired with filtration, sorption, membrane methods, flotation and oxidation, so that the removal load is distributed across several stages and the weaknesses of any single method are partly offset [7, 8].

A separate line of work concerns soft sensors and statistical models for the control of treatment facilities, aimed at inferring quantities that are hard to measure directly and at detecting deviations earlier [9, 15]. Such tools depend on a large and reliable experimental dataset and do not replace physical sensors or laboratory analysis.

On this basis the present work proposes a modular scheme in which the composition and sequence of units are matched to a specific effluent, the required throughput and the planned direction of reuse.

1.2. Aim and objectives

The aim is to develop the concept and functional architecture of a modular electrochemical system for wastewater treatment and regeneration that can be built into a smart mobile home, an off-grid residential complex or an industrial facility. The object of the study is a modular water treatment system as part of the engineering infrastructure of an intelligent real estate facility; the subject is the composition of its modules, their functional links, configuration options and means of incorporating the complex into an automated control system.

Three objectives follow. The first is to establish a functional structure of technologically self-contained modules and define the purpose and interconnections of each unit. The second is to map effluent classes onto specific module sequences, so that the claim of configurability becomes a testable proposition rather than a declaration. The third is to set out the monitoring architecture and a programme of experimental verification for the complex.

2. Materials and Methods

2.1. Nature of the work and source materials

This work is conceptual, design-oriented and review-analytical. No independent laboratory or industrial testing of treatment quality was carried out, and the article therefore reports no removal efficiencies, energy consumption figures, electrode or sorbent service lives, waste quantities, monitoring accuracy or life-cycle costs. All such quantities are identified in Section 4.7 as the subject of subsequent verification.

The source materials were scientific publications on electrochemical water treatment and electrocoagulation; studies of chemical precipitation, sorption, ion exchange, filtration and combined methods; publications on automated monitoring and data analysis at treatment facilities; technical descriptions and layout materials for the installations considered; and materials from the author’s concept of smart real estate infrastructure [1].

The photographs in Figures 2 and 3 show commercially available equipment of the type assumed in the design and are reproduced as illustrations of a possible physical layout only. They are not evidence of treatment performance and do not depict a built prototype of the system proposed here.

2.2. Methods applied

Known treatment methods were compared across reagent consumption, secondary waste generation, pH dependence, potential for reuse, operating costs and compatibility with automated control. Functional decomposition then divided the water treatment process into eight self-contained operations: collection and equalization, preliminary filtration, sorption, flotation separation, electrochemical treatment, ion exchange, final mechanical polishing, and monitoring and control. Systems analysis was used to establish the links between the resulting modules and the conditions under which the complex fits into the engineering infrastructure of a facility, and variant design was applied to derive the configurations given in Section 3.3. A preliminary techno-economic assessment was based on the assumed equipment set, module unification and indicative prices for consumables.

2.3. Criteria for forming the modular architecture

The architecture was shaped around six criteria: functional independence of each module, allowing individual units to be serviced or replaced; freedom to change the sequence of operations; compatibility of hydraulic interfaces; scalability of throughput; connection of local controllers to a higher-level system with real-time data collection; and suitability for integration into both stationary and mobile facilities. These are design requirements, and whether they are met must be confirmed when a prototype is built and tested.

3. Results

3.1. Conceptual architecture of the system

Functional decomposition yielded an architecture of seven technologically self-contained equipment types: storage and equalization tanks (1), filtration and sorption modules (2), an aerodynamic turbo-flotation unit (3), an electrochemical reactor (4), an ion-exchange column (5), automatic self-cleaning mechanical filters (6), and a monitoring and control unit (7). Each unit can operate within the complete complex or be connected to an existing process line as a stand-alone element. The water, signal and residual streams linking them are shown in Figure 1.

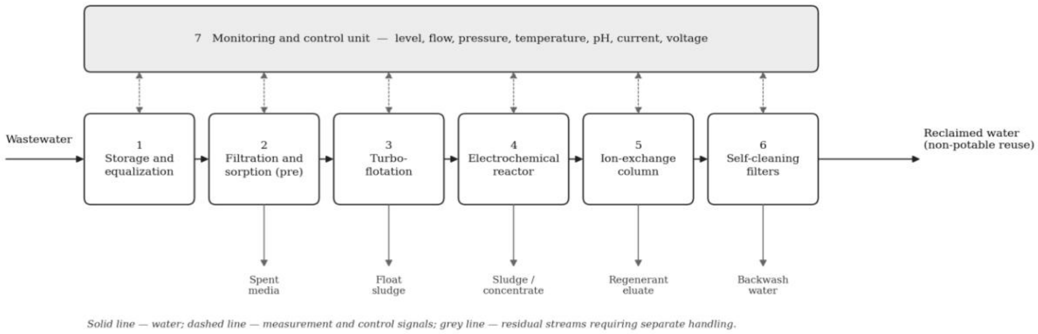

Fig. 1. Process flow of the seven-module architecture. Module numbering is used throughout Section 3 and in Table 1.

3.2. Composition and intended functions of the modules

Storage and equalization tanks (1) receive incoming water, hold it and equalize its composition before it is fed forward. They carry level, temperature and pH sensors, mixing, connection to pumps and standard pipeline fittings.

Filtration and sorption modules (2) are provided in two roles. The preliminary module strips out mechanical impurities and protects the downstream equipment; the final module polishes the water to parameters at which it can be returned to technical service. The composition of the sorption medium is selected for the water in question and confirmed by testing.

The aerodynamic turbo-flotation unit (3) creates a gas-liquid medium and removes dispersed pollutant particles. An upward flow combined with a distributed gas phase is intended to provide flotation removal of part of the suspended matter; bubble size, residence time and the maximum hydraulic load are to be obtained through testing.

The electrochemical reactor (4) carries the main workload. Its design decisions are volumetric porous electrodes of carbon-carbon material, treatment in an upward flow, adjustable interelectrode spacing, regulated current density, vortex elements at the inlet or outlet, and connection of current, voltage, temperature and pH sensors. The developed surface of a porous electrode increases contact area with the medium and should in principle outperform a flat electrode; how far this holds in practice depends on current density distribution, solution conductivity, the stability of the hydrodynamics and the rate at which pores foul.

The ion-exchange column (5) removes residual ions using cation exchangers, anion exchangers or natural sorption materials, with working capacity, cycle length and regeneration conditions set according to the water composition. Automatic self-cleaning filters (6) provide coarse and fine mechanical treatment and protect the downstream modules; the self-cleaning function shortens downtime, while backwash frequency and wash water volume remain to be established.

The monitoring and control unit (7) aggregates data from local sensors and provides level monitoring, flow and pressure measurement, temperature and pH measurement, current and voltage logging, control of treatment duration, control of pumps, valves and power supplies, and data transfer to the supervisory level.

Fig. 2: Ion-exchange columns combined with automatic self-cleaning mechanical filters (modules 5 and 6)

3.3. Effluent classes and corresponding configurations

For the purposes of variant design, wastewater is divided into five groups by metal ion content, and each group is assigned a module sequence using the numbering of Figure 1. The mapping is given in Table 1. It is the author's design proposition rather than a regulatory classification, and the boundaries between groups, along with the performance of each configuration, must be established experimentally.

Table 1: Proposed Module Configurations by Effluent Group

Group	Metal ioncontent	Proposedmodulesequence	Governingmodule
I	notdetectable	1 - 2 - 6	sorptionmedium
II	upto 1 g/l	1 - 2 - 4 - 5 - 6	ion-exchangecolumn
III	1 to 5 g/l	1 - 2 - 3 - 4 - 5 - 6 (fulltrain)	electrochemicalreactor
IV	5 to 10 g/l	1 - 2 - 3 - 4 - 4 - 5 - 6 (reactorsinseries)	electrochemicalreactor
V	above 10 g/l	1 - 3 - 4 - 4 withrecycleloop - 2 - 5 - 6	reactorandsludgehandling

Module numbering follows Figure 1. Repeated numbers denote units in series. Compiled by the author.

The logic of the mapping is that the electrochemical reactor is engaged only where dissolved metals are present in quantity, while ion exchange serves as a polishing stage rather than a primary removal step. At the highest concentrations the reactor is placed ahead of the sorption stage to avoid rapid exhaustion of the medium, and a recycle loop is introduced so that residence time can be extended without enlarging the reactor.

3.4. Capacity and scaling

Individual modules are envisaged in a design range from 500 to 1500 l/h in 250 l/h increments. These are design sizes, not confirmed operating characteristics. The throughput of the complex as a whole is governed not by the maximum flow rate of its most powerful unit but by the capacity of the most restrictive link in the chain, the treatment duration and the volume of the intermediate tanks.

Fig. 3: Water treatment and regeneration system with electrochemical reactors and filtration modules

3.5. Monitoring, adaptive control and resonant impedance sensing

Each module is fitted with a local controller that collects data, executes basic control algorithms and passes information to the supervisory level. Once a sufficient body of experimental data has accumulated, soft sensors and machine learning algorithms may be applied to detect deviations in feed water composition, predict the quality of the treated stream, identify filter fouling, assess electrode condition, optimize energy consumption and detect faults [9, 15]. At the initial stage an operator support system is the appropriate scope: safety-critical control and emergency protection must be executed by standard algorithms independent of any model. The neural network architecture, training sample, learning algorithm and accuracy metrics are not presented in this work, and artificial intelligence is accordingly treated as a development direction rather than implemented functionality.

Resonant impedance sensing is proposed as an auxiliary instrument. The term denotes a contactless method of recording changes in the frequency characteristics of a resonant circuit brought about by the electrophysical properties of the medium, using several channels at different frequencies to yield a multi-frequency profile. Its attraction is that the sensing element makes no direct contact with contaminated water, monitoring is continuous, the signal is obtained rapidly, and deviations can be detected between laboratory analyses.

The difficulty is that the frequency response reacts simultaneously to temperature, conductivity, total dissolved solids, the concentration of various ions, organics, gas inclusions and the geometry of the measuring section, all of which are mixed into a single signal. Quantitative use therefore requires the working frequencies to be determined, calibration to be performed, sensitivity and the limit of detection to be established, selectivity to be assessed, repeatability to be verified and the results to be compared with laboratory analytical methods. Until then the method serves as an indicator of deviation, not as a source of concentration data [1, 16].

3.6. Integration into smart mobile home infrastructure

Building the complex into a smart mobile home introduces constraints that stationary industrial installations do not face: permissible equipment mass, dimensions and energy consumption in the first instance, and beyond these the vibration loads arising when the facility is moved, noise, freeze protection, the volume of storage tanks, access for maintenance, and sanitary requirements governing reuse.

Streams should be separated in advance. Within the proposed concept, greywater and technical effluent are the priority treatment targets; domestic blackwater requires a self-contained sanitary loop with disinfection and confirmation of regulatory compliance, and is not put forward as a function of this system. Regenerated water is intended for non-potable duties such as technical washing, irrigation and the servicing of engineering systems. Potable and sanitary use is inadmissible without specialized additional treatment and confirmed laboratory monitoring.

3.7. Preliminary techno-economic assessment

The modular design allows assemblies to be unified and capacity to be added in stages, though the effect of production volume on unit cost, transport and installation was not quantified. The indicative cost of the equipment set, comprising the seven modules, instrumentation, the control system, connecting elements and an initial stock of consumables, is of the order of USD 65,000. This figure is a design estimate: it is not supported by a full specification, does not include verified installation and commissioning costs, and does not account for life-cycle cost. A qualitative comparison of the approaches considered is given in Table 2.

Table 2: Qualitative Comparison of Wastewater Treatment Methods

Parameter	Chemical methods	Proposedmodularelectrochemicalsystem
Reagents	Coagulants, alkalis or acids must be dosed depending on the process	Continuous reagent consumption may be reduced; sorbents, ion-exchange materials and cleaning solutions may still be required
Secondarywaste	Precipitates and sludge are generated	Precipitates, concentrates and spent materials may form; their quantity requires verification
pH dependence	The operating pH range substantially affects efficiency	Efficiency may also depend on pH, conductivity and electrode process parameters
Water reuse	Possible once the required quality indicators are met	Partial or closed-loop circulation is envisaged once water quality is confirmed
Operatingcosts	Reagents, sludge handling and disposal, maintenance	Electricity, electrodes, sorbents, regeneration, maintenance and waste disposal
Automation	Feasible with standard process control equipment	Local controllers are integrated; the use of AI requires experimental data
Technology status	Industriallyestablishedmethods	Conceptual design architecture requiring pilot testing

Source: compiled by the author on the basis of [2-5, 7, 11-14, 17].

4. Discussion

4.1. Comparison with chemical methods

Chemical precipitation, coagulation and flocculation are long-established methods capable of handling large volumes of water; with the right choice of reagents and pH, dissolved components are converted into an insoluble form and the sludge is separated [2, 5, 17]. Their operational signature is continuous reagent consumption and secondary waste whose composition and volume depend on the effluent, the reagent dose and the precipitation conditions, and which must be dewatered, transported and disposed of.

Electrochemical treatment can reduce the consumption of some reagents but does not eliminate waste: the pollutants pass into sludge, a concentrate, a sorption layer or another separable product. The advantage of the proposed architecture is therefore a potential reduction in reagent load and the ability to combine several operations flexibly, rather than the absence of reagents or waste.

4.2. Comparison with conventional electrocoagulation

In conventional electrocoagulation, current passes through an electrochemical cell and the electrode processes promote the formation of coagulating compounds, destabilization of colloidal particles, adsorption, precipitation and flotation separation [3, 4, 10-14]. The distinguishing feature of the present concept is that the reactor is embedded in a broader chain, operating alongside filtration, sorption, flotation, ion exchange and final polishing, which allows process functions to be distributed among several units.

A demonstrable comparison, however, rests on four quantities: specific energy consumption, operating current density, pollutant removal efficiency, and electrode consumption together with the rate of passivation. Published values for textile and inorganic effluents place electrocoagulation in the range of several kWh per cubic metre at current densities of tens of amperes per square metre [11, 14], and it is against figures of this kind that the proposed configuration will have to be measured. Until that is done, no claim of superiority over existing electrocoagulation installations can be sustained.

4.3. Advantages and limitations of the modular architecture

The chief potential advantage is functional modularity: the sequence of operations can be changed, only the units required need be connected, throughput can be scaled, and individual modules can be replaced or added to existing lines in stages. Combining electrocoagulation with filtration, membrane, sorption and oxidation processes broadens the range of pollutants that can be removed [7, 8].

The flip side is complexity. As the number of modules grows, so does the number of connections, pumps, valves, sensors and control elements, bringing additional hydraulic losses and more points at which leaks and failures can occur. For modularity to deliver its benefits, interfaces must be standardized and the throughput of adjacent units matched.

4.4. Limits of reagent independence

The description "reagent-independent system" needs qualifying. Operating the complex calls for ion-exchange resins, sorbents, activated carbon, washing solutions, media regeneration agents, scale removal formulations and materials for cleaning or replacing electrodes. Electrode material consumption, passivation, energy consumption and sludge formation are significant factors for any electrocoagulation system [3, 7, 11, 14]. The system is therefore more accurately described as aimed at reducing reagent dependence than at eliminating it.

4.5. Potential for water reuse

Water reuse reduces both fresh water consumption and discharge volumes, but whether recirculation is possible depends on how far the water quality matches the requirements of the specific application [7, 17]. Assessment calls for monitoring of target metal content, chemical and biochemical oxygen demand, suspended solids, conductivity, total dissolved solids, pH, turbidity, organic components, microbiological indicators and electrode reaction products. The phrase "complete water recirculation" is inaccurate without supporting data, since some water is inevitably lost with sludge, concentrates, wash streams and evaporation.

4.6. Practical significance

The architecture can serve as a basis for designing a pilot installation at electroplating plants, metallurgical production sites, local industrial streams, agricultural facilities, off-grid residential complexes and smart mobile homes. Electrocoagulation is also being studied in relation to pharmaceutical wastewater, though use in medical institutions would require specialized testing and confirmation of sanitary safety [18].

4.7. Limitations and programme of verification

The principal limitation of this work is the absence of the author's own experimental data. Further work should proceed in four stages. Individual modules are tested first, to determine each unit's contribution to the change in water quality along with its throughput, hydraulic characteristics and service life. Different module sequences are then tested as a complete complex on model solutions and real effluents, recording in each operating mode:

- pollutant concentrations before and after treatment;
- pH andconductivity;
- flow rate and current density;
- specificenergyconsumption;
- wastequantityandcomposition;
- electrode and media service life, and the rate of passivation.

Pollutant removal efficiency is calculated as:

$$\eta = ((C_0 - C_1) / C_0) \times 100\ \% \qquad (1)$$

where η is removal efficiency, %; C_0 is the initial concentration; and C_1 is the concentration after treatment.

Specific energy consumption is defined as:

$$E_s = W / V \qquad (2)$$

where E_s is specific energy consumption, kWh/m³; W is the energy consumed, kWh; and V is the volume of water treated, m³.

The third stage covers the monitoring system: sensors are calibrated and their sensitivity, selectivity and repeatability determined, along with the influence of accompanying parameters such as temperature and conductivity. Only once this dataset exists can intelligent analysis models be developed and tested. The fourth stage is a life-cycle assessment covering production, installation and commissioning, electricity, electrodes, sorbents and ion-exchange materials, maintenance, waste disposal, laboratory monitoring and service life. Each test series must be repeated so that measurement uncertainty and statistical reproducibility can be reported, and results must be compared against a baseline reagent technology treating the same effluent.

5. Conclusion

1. A conceptual architecture has been developed for a modular system for the treatment, regeneration and reuse of wastewater, comprising seven functional equipment types whose water, signal and residual streams are defined in Figure 1.
2. Five effluent groups have been mapped onto specific module sequences (Table 1), converting the general claim of configurability into a set of testable design propositions. The boundaries between groups and the performance of each configuration require experimental confirmation.
3. The modular principle allows the order of operations to be changed, capacity to be increased in stages and individual units to be built into existing infrastructure, at the cost of a greater number of connections, sensors and potential failure points.
4. For a smart mobile home the system is intended for greywater and technical effluent. Blackwater requires a separate sanitary loop with disinfection and lies outside the scope of this article.
5. Resonant impedance sensing and machine learning are development directions, not implemented functions. Both become quantitatively usable only after calibration against laboratory methods and the accumulation of an experimental dataset.
6. The advantages claimed, namely reduced reagent dependence, less secondary waste, closed-loop reuse and cost savings, remain hypotheses to be verified on a prototype under the programme set out in Section 4.7.

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