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# PROCESS INTENSIFICATION IN CONTINUOUS ELECTROCOAGULATION: DESIGN AND EXPERIMENTAL TESTING OF A VERTICAL PSEUDO-SINUSOIDAL FLOW REACTOR

Efficient industrial wastewater treatment in continuous-flow systems requires short hydraulic residence times (RT) without compromising operational stability. Conventional electrocoagulation (EC) reactors often struggle with long RTs, uneven flow distribution, and significant electrode wear. This study introduces a novel serial vertical pseudo-sinusoidal-flow EC reactor (SVPS) featuring hot-swap modular electrodes that guide wastewater sequentially through ten interconnected cells. This innovative design increases effective RT, facilitates beneficial in-situ floc formation, and ensures uniform coagulant utilization throughout the entire treatment process. Laboratory experiments compared this serial configuration against a traditional parallel-flow EC prototype using a flow rate of 1 $m^3$/h and a current density of 10 mA/$cm^2$. The research findings revealed that while the SVPS achieves a cumulative RT equivalent to parallel systems, it offers superior hydraulic uniformity and significantly less short-circuiting. Furthermore, the SVPS reduces electrode stress and provides more homogeneous treatment. Ultimately, this staged design outperforms conventional reactors, providing a compact, energy-efficient, and scalable solution for real-time industrial wastewater recycling and reuse.

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## 1. INTRODUCTION

The treatment and recycling of industrial wastewater in continuous-flow processes, particularly in food-processing and agro-industrial plants, require rapid and efficient pollutant removal under very short hydraulic residence times (RT). In these systems, conventional equalization basins or storage reservoirs are often impractical due to space limitations, hygiene requirements, and the need for uninterrupted production [1–3]. Insufficient RT in traditional treatments frequently leads to incomplete colloid destabilization, weak floc formation, and poor clarification, thereby limiting the potential for water reuse.

Electrocoagulation (EC) is a well-established technology capable of removing suspended solids, pigments, organic matter, and heavy metals through the in-situ generation of metal hydroxide coagulants from sacrificial iron or aluminum electrodes [4–6]. By eliminating the need for chemical dosing and producing easily settleable flocs, EC is particularly suitable for on-site industrial wastewater treatment. However, conventional EC reactors typically operate in batch or semi-batch modes with extended RTs (10–40 min), making them unsuitable for immediate recycling in continuous-flow operations [7, 8]. Increasing current density can shorten RT by accelerating coagulant production but simultaneously accelerates electrode wear, intensifies Joule heating, and promotes parasitic electrolysis reactions, compromising both energy efficiency and operational stability [9, 10].

Beyond electrochemical limitations, hydraulic design plays a critical role in treatment efficiency. Residence time depends not only on reactor volume but also on flow path geometry, velocity distribution, and laminarity. Conventional parallel-flow arrangements, where influent is divided among multiple cells, often experience uneven flow distribution, short-circuiting, and local hotspots, which reduce floc growth and clarification efficiency [11–15]. Compact reactors employing elongated or tortuous flow paths can increase effective RT without enlarging the footprint while maintaining laminar conditions and minimizing short-circuiting.

To overcome these challenges, this study presents a continuous serial vertical pseudo-sinusoidal-flow (SVPS) EC reactor equipped with hot-swap modular electrodes. The design combines a compact multi-cell architecture with a vertically alternating hydraulic path, forcing wastewater sequentially through ten interconnected cells. This SVPS trajectory increases cumulative RT, promotes progressive floc formation and in-situ decantation, and ensures uniform coagulant utilization. Hot-swap electrodes allow maintenance without interrupting operation, while parallel electrical connections distribute voltage evenly, minimizing localized electrode stress.

A laboratory-scale experimental investigation is conducted to evaluate the hydraulic and electrochemical performance of the SVPS configuration and to compare it with a conventional parallel-flow prototype under identical total flow (1 $m^3/h$) and current density ( rasting staged, cumulative exposure in the SVPS path with single-pass exposure in parallel channels, this work highlights the benefits of hydraulic sequencing and progressive coagulant utilization in continuous EC treatment.

## 2. REACTOR DESIGN AND OPERATING PRINCIPLES

The reactor in both configurations (parallel and proposed SVPS) is composed of ten hydraulically interconnected cells, each with a 20×20 cm cross-section area, equipped with flat (Fe/Al) plate electrodes mounted on lateral sliding rails.

*Parallel path configuration.* In the parallel path configuration, the influent stream is evenly distributed at the reactor inlet and divided into ten identical hydraulic paths, each feeding one cell independently (Fig. 1). All cells operate under the same hydraulic residence time and receive wastewater simultaneously. The electrodes in each cell are electrically connected in parallel to a common DC power supply, resulting in identical applied voltage but a division of the total current among the cells.

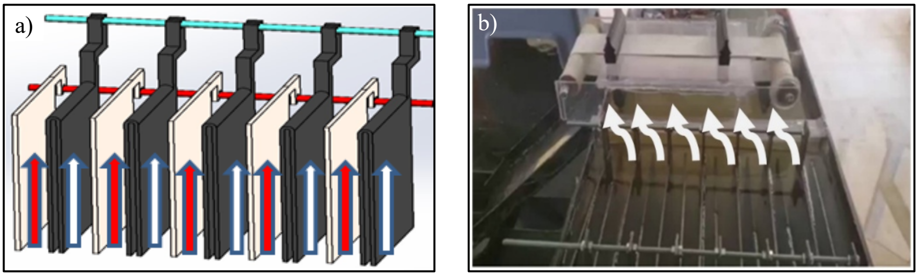


Fig. 1. Parallel path configuration: a) principal, b) prototype

*Proposed SVPS path configuration.* In the SVPS path configuration (Fig. 2), the influent enters the first cell and is forced to flow successively through all ten cells along a vertically oriented, alternating flow path. The hydraulic design imposes repeated changes in flow direction, creating a pseudo-sinusoidal trajectory that effectively elongates the hydraulic pathway within a compact footprint. As a result, the same volumetric flow rate experiences a substantially increased effective residence time without increasing reactor volume. The electrodes are electrically connected in parallel, ensuring that each plate receives the same voltage while sharing the total current.

This mechanical arrangement allows electrodes to be hot-swapped without draining the reactor or interrupting operation. Each plate serves a dual purpose: as a hydraulic baffle, directing wastewater along a vertical pseudo-sinusoidal trajectory, and as an electrochemical electrode, generating $Fe^{3+}$ or $Al^{3+}$ coagulants. Figure 2b demonstrates how this geometry effectively increases hydraulic residence time without enlarging the reactor volume, while maintaining laminar flow, preventing short-circuiting, and activating both faces of each electrode to double the electrochemically active surface area.

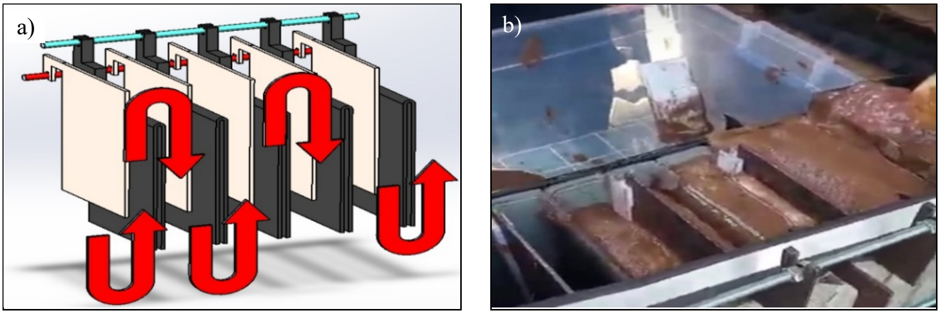


Fig. 2. Proposed SVPS path configuration: a) principal, b) prototype

In the SVPS flow, beneath each anodic electrode, the reactor basin incorporates a localized lower extension that forms a sedimentation pocket. This geometry promotes in situ gravitational decantation under low-Reynolds-number conditions (Fig. 3).

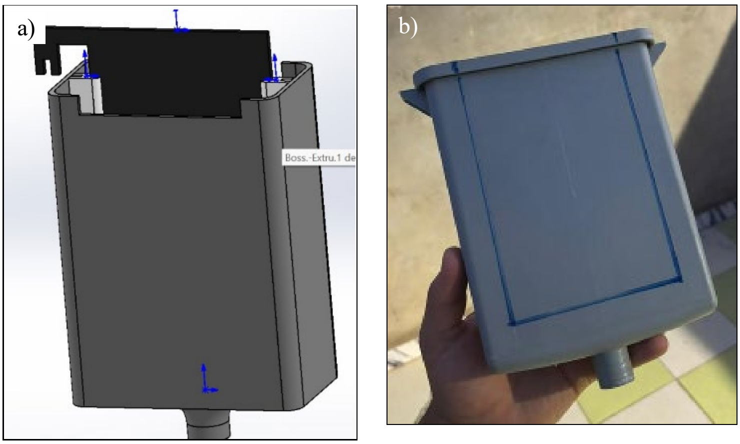


Fig. 3. Elementary reactor basin with sedimentation pocket under the anodic electrode: a) principal, b) prototype

As flocs formed near the anodic surfaces, they entered the expanded cross-section beneath the electrode, where the flow velocity decreased significantly. The resulting reduction in the Reynolds number creates hydrodynamically quiescent zones that suppress turbulence and prevent re-entrainment. Dense aggregates settled naturally, whereas clarified water was gently redirected upward toward the next cell. This mechanism, reinforced by the SVPS path, enables progressive solid–liquid separation within each cell and eliminates the need for external settling basins.

## 3. TESTS AND RESULTS DISCUSSION

Two electrocoagulation reactor prototypes were evaluated, built with identical electrodes, spacing, and total flow rate. The conventional parallel-flow configuration (Fig. 4) divides the influent into multiple streams passing simultaneously through electrode gaps, representing a conventional continuous EC setup. The SVPS configuration (Fig. 5) forces the entire flow sequentially through all cells, increasing cumulative residence time while maintaining the same total flow and electrical conditions. Figures 4 and 5 illustrate the distinct hydraulic pathways, forming the basis for the comparative analysis of treatment efficiency, residence time, energy consumption, and electrode stress.

Fig. 4. Electrocoagulation treatment prototype using a conventional parallel-flow configuration

Fig. 5. Electrocoagulation treatment prototype using SVPS configuration

All comparative analyses between the SVPS configuration and the parallel-flow configuration were performed under the constraints of an identical total volumetric flow rate (1 $m^3/h$) and an identical total applied current, with all anodes electrically connected in parallel and all cathodes electrically connected in parallel in both cases. This ensures that the electrochemical driving force and overall treatment capacity are strictly comparable.

Under these conditions, the two configurations differ fundamentally in their hydraulic organization. In the parallel-flow reactor, the total flow is divided among multiple electrode gaps operating simultaneously, resulting in a relatively low linear velocity within each gap. Each water parcel undergoes electrocoagulation only once, during a single residence time associated with one electrode gap. In contrast, in the SVPS configuration, the entire flow passes sequentially through all electrode gaps, which necessarily leads to a higher local flow velocity in each individual gap in order to maintain the same total throughput.

Despite this increase in instantaneous velocity, the SVPS configuration provides a decisive advantage: each water parcel is exposed repeatedly to electrocoagulation across successive gaps. Consequently, the effective hydraulic residence time is cumulative, equal to the sum of the residence times of all individual gaps.

Output water ← Treated water ← Reactions ← Serial reactors ← wastewater

Fig. 6. Experimental test results using SVPS-EC configuration

Because the total current is identical in both configurations and distributed over the same number of electrodes, the current per electrode remains unchanged. Consequently, the intrinsic current density and Joule losses are comparable at the electrical level. In the serial configuration, however, this identical electrochemical input is exploited more efficiently through hydraulic staging: coagulant generation, pollutant destabilization, and floc growth proceed progressively across successive gaps rather than during a single hydraulic pass (Fig. 6). This sequential exposure limits the need for aggressive electrochemical conditions, reduces localized electrode stress, and promotes more uniform treatment. As a result, despite higher local flow velocities, the SVPS configuration delivers superior treatment performance and greater operational stability under the same total current and flow constraints. The observed performance enhancement, therefore, stems from hydraulic sequencing and cumulative residence time, not from increased electrical energy input.

## 4. COMPARATIVE LABORATORY EXPERIMENTS

Comparative laboratory experiments conducted under strictly identical total flow rate and applied current revealed marked differences in internal hydrodynamics and treatment behavior. While global operating conditions were equivalent, the internal flow organization strongly influenced residence time distribution, coagulant utilization, and floc development. The SVPS configuration ensured continuous, staged exposure of the wastewater to the electroactive surfaces, whereas the conventional parallel-flow reactor proved more susceptible to flow maldistribution. These experimentally established differences underpin the comparative assessment presented in Table 1.

Table 1

Experimental test results parallel EC flow vs. SVPS flow EC

| Parameter | Parallel flow | Serial flow (SVPS) | Comment |
|---|---|---|---|
| Flow per electrode, $m^3/s$ | $2.78\times10^{-5}$ | $2.78 \times 10^{-4}$ | serial passes total flow through each gap |
| Velocity per gap, m/s | 0.00278 | 0.0278 | higher linear speed in serial gap, shorter RT per cell |
| RT per cell, s | 108 | 10.8 | cumulative RT = 108 s for serial flow |
| Total RT, s | 108 | 108 | same total RT, but distributed differently |
| Current per electrode, A | 4 | 4 | parallel wiring in both cases |
| Coagulant mass per electrode, g | 0.083 | 0.083 | identical total production |
| Hydraulic uniformity | lower | higher | serial prevents short-circuiting |
| Short-circuiting risk | high | minimal | flow in parallel channels may bypass some gaps |
| Floc formation | partial, uneven | progressive, in-situ | sedimentation pockets in serial |
| Electrode stress and Joule losses | higher locally | lower, uniform | serial distributes energy more evenly |
| Treatment efficiency | moderate | high | serial favors complete destabilization |

The SVPS configuration introduces a hydraulic uniformity. The vertical sinusoidal path increases effective residence time per unit volume, forces the water through alternating upward and downward flows, and isolates sedimentation pockets beneath anodic electrodes, where flocs form and settle in situ under low Reynolds number conditions. This ensures progressive solid-liquid separation, minimizes resuspension, and improves coagulant utilization. Joule losses are more evenly distributed, and the electrode stress is lower, reducing local overheating and extending electrode lifetime.

## 5. CONCLUSION

The study demonstrates that an SVPS with hot-swap modular electrodes offers significant advantages over conventional parallel-flow configurations for industrial wastewater treatment. Laboratory-scale tests confirmed that, under identical total flow (1 $m^3/h$) and total current (10 $mA/cm^2$), the SVPS configuration achieves cumulative residence times comparable to parallel flow, while promoting progressive in-situ floc formation, sedimentation, and uniform coagulant utilization.

The SVPS hydraulic path enhances residence time distribution and hydraulic uniformity, minimizes short-circuiting, and forces sequential exposure of wastewater to electrocoagulation across multiple cells. As a result, treatment efficiency is increased, local electrode stress and Joule losses are reduced, and the electrochemical input is utilized more effectively than in parallel-flow systems.

By integrating hydraulic sequencing with low-stress electrical operation, the reactor enables stable, energy-efficient, and continuous operation without requiring large equalization tanks or interrupting industrial processes. These findings provide a robust framework for scaling up SVPS EC systems for real-time industrial wastewater recycling and highlight the importance of intelligent hydraulic-electrochemical coupling in next-generation continuous electrocoagulation technologies.

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