Coupled Research on Membrane Concentration and Chemical Regulation in Wastewater Treatment Systems

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Abstract: ***With the transformation of wastewater treatment towards resource utilization and green development, single treatment technologies are no longer sufficient to meet the requirements of efficient removal and reuse of complex pollutants. To improve the efficiency of complex wastewater treatment and the level of resource recovery, the coupled treatment technology of membrane concentration and chemical regulation was systematically studied. By analyzing the basic principles and synergistic mechanisms of membrane concentration and chemical regulation, their treatment effects on various typical industrial wastewaters were explored. The results show that the coupled technology can significantly improve the pollutant removal rate, reduce the risk of membrane fouling, and exhibit good application potential in resource recovery and emission reduction. It is pointed out that there are problems such as difficult parameter optimization and insufficient intelligent control in the current process, and an optimization path from multi-parameter coordinated regulation and intelligent management is proposed. This provides a theoretical basis and engineering reference for the application of membrane-chemical regulation technology in the advanced treatment and resource utilization of wastewater, and conducts a systematic study on the coupled technology of membrane concentration and chemical regulation in wastewater treatment systems. The basic principles and coupling mechanisms are sorted out, the actual effects under typical wastewater types are analyzed, the existing problems in the current coupling of membrane concentration and chemical regulation are analyzed, and an optimization path is proposed, aiming to provide theoretical support and technical reference for the in-depth application and industrial promotion of such technologies.***

Keywords: Membrane Concentration; Chemical Regulation; Coupled Technology; Wastewater Treatment.

1. INTRODUCTION

In the context of the increasing emphasis on current environmental governance and resource recycling, wastewater treatment technologies are evolving from the traditional pollutant removal function towards efficient purification, resource recovery and green sustainability. Especially in the treatment of typical industrial wastewater with high salt, high organic load and heavy metals, traditional processes such as conventional biochemical methods and precipitation methods are no longer sufficient to meet the strict discharge standards and reuse requirements. Therefore, exploring efficient, controllable and adaptable composite treatment technologies has become an important development trend in the field of wastewater treatment.

2. PRINCIPLE OF THE COUPLING TECHNOLOGY OF MEMBRANE CONCENTRATION AND CHEMICAL REGULATION

2.1 Basic Principles of Membrane Concentration Technology

Membrane concentration technology is a physical treatment process based on the principle of selective separation of semi-permeable membranes, and is widely used in the concentration of substances and the reuse of water resources in wastewater treatment. Common membrane separation methods include nanofiltration, reverse osmosis, and ultrafiltration, which mainly achieve pollutant interception and water penetration under pressure drive through the differential permeability of the membrane material to solutes and solvents. The membrane concentration process has the advantages of low energy consumption, high separation efficiency, and simple operation. However, when operating at high loads or treating complex wastewater, problems such as membrane fouling and difficult treatment of concentrated liquid are likely to occur. Therefore, single membrane concentration often needs to be supplemented by other means in engineering practice to ensure the stable operation of the system. Wang and Lai (2026) proposed a novel strategy to enhance upper-room ultraviolet germicidal irradiation (UVGI) performance by employing a rotating UV source under poorly-mixed ventilation conditions, which could effectively improve disinfection efficacy in spaces with uneven airflow [1]. Narouei et al. (2025) investigated the effects of germicidal far-UVC (222 nm) on ozone and particulate matter in a conference room, finding that the irradiation not only inactivates microorganisms but also induces secondary chemical reactions that alter ozone and particle concentrations, highlighting important implications for indoor air quality [2]. Xiao et al. (2022) developed an ultrasmall Fe_3O_4-decorated polydopamine hybrid nanozyme that enables continuous conversion of oxygen into toxic hydroxyl radicals via a glutathione-depleted cascade redox reaction, and they demonstrated its intensive wound disinfection capability with promising biocompatibility [3].

2.2 Overview of Chemical Regulation Methods

As a key auxiliary means in the wastewater treatment process, chemical regulation mainly changes the physical and chemical properties of pollutants in water to enhance their separability or reduce their adverse effects on the treatment system. Common chemical regulation means include pH adjustment, redox reactions, complexation/chelation reactions, and flocculation precipitation. While chemical regulation can adjust the quality of wastewater and improve treatment adaptability, it may also bring problems such as drug residues, secondary pollution, or increased operating costs. It is necessary to achieve a reasonable coupling with membrane technology to fully exert its advantages.

2.3 Analysis of the Coupling Mechanism

There is a significant synergistic effect between membrane concentration technology and chemical regulation means. On the one hand, in the coupling process, chemical regulation can be used as a pretreatment or synchronous treatment link for membrane separation. By improving the quality of wastewater and reducing the pollutant load, the occurrence of membrane fouling can be effectively slowed down [3]. On the other hand, the high selectivity of the membrane separation process can also enhance the effect of chemical regulation. For example, intercepting harmful intermediate products that have not reacted completely to improve the overall treatment quality. The coupling of membrane concentration and chemical regulation is not only a simple superposition of physical separation and chemical regulation, but also a system optimization strategy that achieves multi-dimensional complementarity in reaction paths, operating parameters and treatment objectives. The process flow diagram of the coupling system is shown in Figure 1.

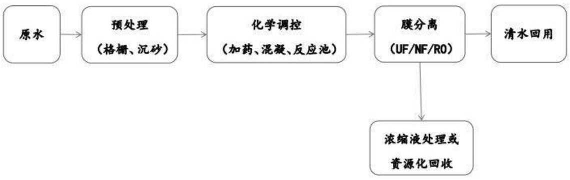

Figure 1: Process Flow Diagram of the Membrane Concentration and Chemical Regulation Coupling System

3. COUPLING OF MEMBRANE CONCENTRATION AND CHEMICAL REGULATION IN WASTEWATER TREATMENT SYSTEMS

3.1 Synergistically Improve the Pollutant Removal Efficiency

The membrane separation process is based on the selective separation characteristics of the semi-permeable membrane. It mainly retains solutes and allows water to pass through by pressure driving, achieving effective retention of pollutants. Chemical regulation methods, on the other hand, create a better separation environment for the membrane system by reactively adjusting the morphology or stability of pollutants. In the treatment of wastewater containing complex pollutants, it is difficult to efficiently treat colloidal, hydrophilic organic substances and trace heavy metal ions by relying solely on membrane separation. However, this technical shortcoming can be effectively solved through pre-treatment or synchronous chemical regulation. The treatment performance of the membrane system is usually measured by membrane flux, as shown in Equation (1).

$$J = \frac{V}{A \cdot t} \tag{1}$$

In the equation, J is the net water production flux per unit area of the membrane per unit time, $\mathrm{m}^3/(\mathrm{m}^2 \cdot \mathrm{d})$; V is the volume of the permeate collected within time t, m^3; A is the effective area of the membrane, m^2. Membrane flux is synergistically affected by water quality characteristics, pollutant load, membrane material properties and pre-treatment measures.

In the chemical regulation stage, the addition of inorganic or polymer flocculants can promote the aggregation of colloidal and high-molecular organic pollutants into large particles, improving the efficiency of their physical retention by the membrane. Oxidants can convert refractory organic substances into smaller molecules that are easier to remove by destroying conjugated structures and breaking molecular bonds, thus enhancing the membrane treatment effect. For example, when treating benzene-containing organic wastewater with potassium permanganate as an oxidant, its oxidation reaction can be simply expressed as

$$KMnO_4 + Organic \rightarrow CO_2 + Mn^{2+} + H_2O \tag{2}$$

The introduction of chemical regulation significantly changes the particle size distribution and hydrophilic/hydrophobic characteristics of pollutants, effectively reducing the membrane fouling rate and enhancing the system stability. Membrane concentration and chemical regulation technologies complement each other in the dimension of pollutant removal and work synergistically in the same treatment process, especially suitable for the deep purification requirements of wastewater with complex composition and high concentration.

3.2 Enhancing the Treatment Adaptability of the System to Complex Water Quality

Industrial wastewater comes in a wide variety, often containing multiple types of pollutants such as organic matter, heavy metals, high salinity, and surfactants. The water quality volatility and compositional complexity pose serious challenges to the membrane system. After coupling with a chemical regulation unit, the system's ability to handle sudden changes in water quality can be effectively improved, enhancing the operational flexibility and running stability of the process. During operation, pH value adjustment is one of the common control measures, especially in the treatment of heavy metal wastewater. By adjusting the alkalinity of the system, precipitation reactions of metal ions occur. Such reactions not only prompt the precipitation of metal ions in an insoluble form but also significantly reduce the risk of their deposition on the membrane surface. In the treatment of wastewater containing ammonia nitrogen or sulfides, oxidation regulation can break the structures of ammonia molecules or neutral sulfides, improving their removal efficiency. In the treatment of high-salt wastewater, adding softening agents such as Na_2CO_3, EDTA, etc., can complex or precipitate hardness ions such as Ca^{2+} 、 Mg^{2+}, reducing the risk of fouling in the subsequent membrane section. Table 1 shows the effects of different chemical regulation methods on typical water quality pollution factors.

Table 1: Improvement Effects of Chemical Regulation on the Influent Water Quality of the Membrane System

Regulation method	Main reaction object	Influence index	Improvement result
pH value adjustment	Heavy metals, alkaline/acids	Metal precipitation, corrosivity	Reduce the risk of corrosivity and scaling
Oxidation regulation	Organic matter, ammonia nitrogen	COD, ammonia nitrogen	Reduce the membrane fouling pressure
Flocculation precipitation	Colloids, organic macromolecules	Turbidity, COD	Enhance filtration efficiency and extend membrane life
Softening complexation	Ca^{2+}、Mg^{2+}	Hardness, conductivity	Slow down inorganic scaling

3.3 Support for the Goals of Resource Utilization and Emission Reduction

The integrated application of membrane concentration and chemical regulation technologies can also play an important role in pollutant enrichment, extraction of recyclables, and water resource reuse. The membrane process itself has the advantages of high rejection rate and low energy consumption, and can enrich valuable substances in wastewater, such as heavy metals and organic carbon sources, in the concentrate, and then further achieve recovery or stabilization treatment through chemical regulation. In the treatment of electroplating wastewater, the membrane section can achieve the enrichment of heavy metal ions, and then complete the metal recovery through chemical precipitation. Taking copper ions as an example, its regulation reaction is shown in Equation (3).

$$Cu^{2+} + 2OH^- \rightarrow Cu(OH)_2 \downarrow (\text{沉淀回收}) \tag{3}$$

For wastewater containing organic matter, through front-end oxidation decomposition supplemented by membrane concentration, part of the carbon source can be recovered and used as an energy utilization route such as fermentation and anaerobic digestion. The produced water generated by membrane separation can be directly reused for production cooling, cleaning, etc. after disinfection or advanced treatment, effectively achieving the goal of reuse and emission reduction.

4. PROBLEMS FACED BY THE COUPLING OF MEMBRANE CONCENTRATION AND CHEMICAL REGULATION

4.1 Difficulties in the Synergistic Optimization of Process Parameters

Membrane concentration and chemical regulation technologies are essentially the coordinated operation of two different types of treatment units with different mechanisms. Membrane concentration relies on physical interception, while chemical regulation involves complex chemical reactions and equilibrium processes. During the system coupling process, their key operating parameters are highly intertwined. For example, the pH value, redox potential, reaction time, chemical dosage, etc. during the chemical regulation stage will directly affect the treatment efficiency of the membrane section, the degree of membrane fouling, and the quality of the produced water. Especially in wastewater with a high pollution load, the sensitivities of different pollutants to the chemical dosage strategy and membrane operating conditions vary significantly. If the parameters are not properly matched, it may lead to waste of chemicals, a decline in reaction efficiency, and even the generation of by-products that interfere with the membrane separation process. Parameters such as the operating pressure, flow rate, and recovery rate of the membrane system itself also need to be adjusted synchronously with the chemical process. The operation window is narrow, and manual intervention is frequent, which 极易引发系统不稳定，影响整体处理效果与经济性 [4].

4.2 Lack of Dynamic Monitoring and Intelligent Regulation

The coupling process of membrane concentration and chemical regulation is highly dynamic. Factors such as fluctuations in influent water quality, temperature changes, and the rise and fall of pollution loads can all directly affect the system performance. Under the traditional operation mode, the adjustment of system parameters highly depends on manual experience and regular inspections, resulting in a lag in response and difficulty in accurately adapting to water quality changes. Most small and medium-sized wastewater treatment systems do not have complete online monitoring equipment, leading to the inability to grasp key water quality indicators in real time; the automation functions in the operation of the membrane system, such as intelligent dosing, automatic membrane backwashing, and pressure regulation, are not complete, and the system requires frequent manual intervention, increasing the operation difficulty and maintenance cost [5].

5. OPTIMIZATION PATHS FOR THE COUPLING OF MEMBRANE CONCENTRATION AND CHEMICAL REGULATION

5.1 Optimization Strategies for Process Parameters

The efficient coordinated operation of membrane concentration and chemical regulation depends on the rational configuration of multiple key parameters, including membrane operating pressure, transmembrane pressure difference, flow rate, and recovery rate, etc. It is necessary to introduce more scientific multi-factor collaborative optimization techniques. Statistical and intelligent optimization tools such as response surface method, orthogonal experimental design, or multi-objective optimization algorithm should be used to conduct interaction analysis on the key variables of the coupling system, clarify the influence weights of each parameter on pollutant removal rate, membrane flux, energy consumption, and pollution risk, and construct a systematic regulation model. In actual operation, real-time data should be collected through online sensors, and a regulation system based on an adaptive fuzzy control or neural network prediction model should be established to achieve dynamic optimization regulation of chemical dosing rate, membrane pressure, and cleaning cycle [6].

5.2 Intelligent Control and Process Monitoring

Build a sensor network based on the Internet of Things platform, deploy various online sensors such as pH value, ORP, conductivity, turbidity, COD, membrane flux, and pressure difference to achieve a comprehensive perception of the influent and effluent water quality, chemical dosing status, and membrane operation conditions, as shown in Figure 2. Integrate the intelligent chemical dosing system and the automatic membrane backwashing unit, and dynamically adjust the chemical type and dosing rate based on real-time monitoring data and model prediction results, and regularly start the membrane system backwashing program to extend the membrane service life and avoid resource waste caused by excessive cleaning. Artificial intelligence algorithms and edge computing platforms can be introduced to achieve self-optimizing scheduling [7] driven by data. Combine deep learning models to predict the trend of water quality fluctuations for early intervention; use reinforcement learning algorithms to explore the optimal membrane operation strategy to reduce energy consumption and pollution risks.

6. CONCLUSIONS

The coupling technology of membrane concentration and chemical regulation has shown significant advantages in the advanced treatment and resource utilization of wastewater, effectively improving the pollutant removal efficiency, enhancing the system adaptability, and facilitating reduced emissions and resource recovery. However, this technology still faces a series of challenges at the technical and management levels in practical engineering applications. To address the core issues such as high process coordination difficulty and insufficient intelligent level during the coupling process of membrane concentration and chemical regulation, optimization needs to be carried out from process regulation and system management. With the improvement of module integration and the popularization of digital operation and maintenance platforms, the coupling system of membrane concentration and chemical regulation is expected to be widely deployed in complex scenarios such as high-concentration organic wastewater, heavy metal waste liquid, and urban industrial mixed sewage. Combining AI-assisted parameter scheduling, intelligent dosing systems, and the development of green chemicals will significantly improve the stability and resource utilization efficiency of such systems. Especially in the construction of urban "zero-emission" parks and mobile emergency treatment modules, it has good engineering adaptability and market potential.

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