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Research on Surface Modification Technology of Reverse Osmosis Membranes in Power Plant Water Treatment Systems and Its Anti-fouling Cleaning Efficiency

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Abstract: With the continuous improvement of power plants' requirements for high-quality circulating water and energy conservation and emission reduction, reverse osmosis (RO) membrane systems have become a core technology in water treatment processes. However, membrane fouling is a common problem during long-term operation, leading to membrane performance degradation, increased operational energy consumption, and higher maintenance costs. To enhance the membrane's antifouling performance and cleaning efficiency, this study focuses on membrane surface modification technology, systematically exploring its principles, process applications, and performance characteristics. The research primarily employs three modification techniques: graft polymerization, surface coating, and plasma treatment to regulate the physicochemical properties of membrane surfaces, combined with cleaning performance analysis to evaluate their antifouling effects. All types of modified membranes show significant advantages in improving hydrophilicity, reducing pollutant adhesion, and enhancing cleaning responsiveness. Among them, plasma-treated membranes demonstrate better stability and adaptability, making them suitable for long-term operation under complex water quality conditions. In conclusion, membrane surface modification technology can effectively extend membrane module lifespan, improve the overall operational efficiency of power plant water treatment systems, and provide a practical technical approach for membrane fouling control.

Keywords: reverse osmosis membrane, surface modification, coating technology, plasma, cleaning efficiency

Introduction

Power plants generate large quantities of high-salinity, high-hardness wastewater and circulating water during production processes, which must be purified and recycled through efficient water treatment systems to meet environmental discharge standards and process water quality requirements. Reverse osmosis (RO) membrane technology serves as a critical component for advanced desalination and concentration, featuring high-efficiency separation characteristics, and has been widely adopted in various power plant water treatment systems. However, due to complex feedwater composition, fluctuating operational loads, and biofouling factors, RO membranes are highly susceptible to fouling. Consequently, both academia and industry have recently begun exploring fundamental optimization of membrane material properties to address fouling issues. Among these approaches, membrane surface modification technology has emerged as a research hotspot owing to its advantages of preserving the membrane's bulk structure, strong tunability, and broad adaptability. By adjusting surface parameters such as hydrophilicity, charge density, roughness, and chemical stability, pollutant adsorption rates can be

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effectively reduced, fouling formation delayed, and cleaning efficiency enhanced. Therefore, in-depth investigation of modification mechanisms and their effects holds significant importance for improving RO system operational efficiency and extending membrane service life.

1. Principles of RO Membrane Surface Modification Technology

While RO membranes are extensively applied in water treatment systems, they frequently encounter severe fouling problems during operation, primarily stemming from interactions between membrane surfaces and various impurities in feedwater. Fouling mechanisms are complex, encompassing multiple processes including physical adsorption, chemical reactions, and biological attachment. Physical adsorption involves the accumulation of suspended particles, colloidal substances, and organic macromolecules on membrane surfaces, leading to pore blockage and flux decline. Chemical reactions refer to crystalline deposition of inorganic salts such as calcium carbonate ($CaCO_3$) and silicates (SiO_2), forming irreversible scaling layers. Biological attachment manifests as microbial growth and biofilm formation on membrane surfaces, accelerating fouling and causing rapid performance deterioration. Thus, enhancing membrane antifouling properties constitutes a critical measure for ensuring stable RO system operation and prolonging membrane lifespan, representing a key research direction in membrane technology.

Surface modification technologies employ physical, chemical, or physicochemical methods to construct functionalized layers on membrane surfaces, regulating their chemical composition and physical morphology to optimize interfacial properties. These techniques aim to improve membrane hydrophilicity, reduce surface roughness and energy, and minimize adsorption of hydrophobic organic substances and colloidal particles. Hydrophilicity-enhanced surfaces can form stable water layers, weakening interaction forces between pollutants and membrane matrices. By adjusting surface charge characteristics (e.g., imparting negative charges or modulating charge density), the Coulombic repulsion mechanism can effectively resist adsorption of similarly charged colloids and microorganisms, mitigating colloidal fouling and biofilm formation. Additionally, introducing antibacterial or catalytic functionalities enables active degradation of attached organic pollutants and bacterial growth inhibition (Yang et al., 2020).

Current RO membrane surface modification technologies primarily include chemical graft polymerization, inorganic/organic functional coating construction, and plasma treatment. Chemical graft polymerization utilizes radical or photo-initiated reactions to covalently bond functional polymer chains on membrane surfaces, precisely controlling surface chemistry and hydrophilicity to fundamentally regulate membrane-pollutant interfacial interactions. Inorganic/organic coating techniques deposit nano-inorganic particles or composite polymer layers to enhance mechanical strength and functional diversity, improving antiscaling and antimicrobial properties. Plasma treatment employs high-energy active particles to activate membrane surfaces, generating various polar functional groups that significantly enhance hydrophilicity and surface activity while maintaining environmental friendliness and high efficiency. With advancements in materials science and surface engineering, membrane surface modification is evolving toward multifunctional and intelligent development, enabling precise control and efficient prevention of membrane fouling in complex water quality environments.

2. Application Strategies of RO Membrane Surface Modification Technology in Power Plant Water Treatment Systems

2.1 Graft polymerization process

The graft polymerization process is an advanced modification technique that constructs functional polymer layers on RO membrane surfaces through chemical reactions. Its core principle involves activating membrane surfaces using radical initiators, photoinitiators, or plasma activators to generate highly reactive radical sites, which subsequently initiate monomer polymerization. This results in covalent bonding between polymer chains and the membrane matrix, forming stable and uniform grafted layers. This method not only alters the chemical composition of membrane surfaces but also regulates their physical structure, enabling precise design of surface properties. By adjusting initiator types, monomer concentrations, and reaction conditions, the thickness and functionality of grafted layers can be precisely controlled, maximizing antifouling performance while maintaining fundamental requirements for water flux and selectivity (Chen et al., 2024).

Surface pretreatment is often a critical step in this technology. Pretreatment methods, such as oxygen plasma treatment, chemical oxidation, or UV-ozone treatment, introduce active groups (e.g., hydroxyl or carboxyl groups) onto membrane surfaces, significantly enhancing the efficiency and uniformity of subsequent grafting reactions. Common initiator systems include azo compounds (e.g., AIBN), persulfates, or photoinitiators (e.g., benzophenone derivatives), with the selection based on process requirements. Photoinitiated grafting, performed under UV irradiation, enables low-temperature, solvent-free reactions, making it suitable for heat-sensitive RO membrane materials.

For monomer selection, hydrophilic monomers like acrylic acid (AA), acrylamide (AAm), and polyvinyl alcohol (PVA) contain abundant polar groups, significantly improving membrane hydrophilicity, reducing water contact angles, and minimizing the adsorption of organic pollutants and colloids. Introducing cationic monomers such as quaternary ammonium salts endows membranes with antibacterial activity, inhibiting bacterial adhesion and biofilm formation, thereby further enhancing antifouling capabilities. Recent advancements in multifunctional grafting techniques allow synergistic enhancement of antifouling, antibacterial, and antiscaling properties by combining different monomers, adapting to the complex and variable water conditions in power plants.

During graft polymerization, reaction temperatures typically range from 30 to 60°C, with durations varying from minutes to hours. Precise control of these parameters ensures grafted layer thicknesses of 10–100 nm, balancing high flux performance with layer stability. Post-reaction, thorough washing removes unreacted monomers and residual initiators, preventing water contamination and extending membrane lifespan. Additionally, characterization techniques such as scanning electron microscopy (SEM), contact angle measurements, and Fourier-transform infrared spectroscopy (FTIR) assess graft layer uniformity, chemical composition, and surface energy, ensuring process controllability and stability. This technology significantly improves RO membrane resistance to organic fouling, biofouling, and inorganic scaling during long-term operation, making it a key strategy for enhancing system stability and cost-effectiveness (Chen, Li, Lin, et al., 2024).

2.2 Coating Technology

Coating technology, a pivotal approach for RO membrane surface modification, deposits functional coatings on membrane surfaces through various physical and chemical methods, forming physical barriers or chemical protective layers. This adjusts surface properties to effectively inhibit pollutant adsorption and microbial attachment. The diversity of coating materials offers high process flexibility and adaptability, enabling customized solutions for different fouling challenges in power plant water treatment systems while meeting industrial-scale application demands.

Inorganic nanoparticles, such as titanium dioxide (TiO_2), zinc oxide (ZnO), and silicon dioxide (SiO_2), are mainstream coating materials. TiO_2 nanoparticles exhibit exceptional photocatalytic activity, generating highly reactive hydroxyl radicals under UV light to degrade organic foulants and mitigate flux decline caused by organic accumulation. ZnO nanoparticles demonstrate outstanding antibacterial and UV-resistant properties, inhibiting microbial adhesion and biofilm formation, particularly suited for biofouling control in power plant water reuse systems. SiO_2 nanoparticles primarily modify surface roughness and enhance hydrophilicity, reducing colloidal and particulate fouling. Recently, graphene oxide has emerged as a research focus for next-generation membrane coatings due to its high surface area, superior mechanical strength, and chemical stability, offering combined advantages in antifouling, mechanical reinforcement, and chemical corrosion resistance (Zhu et al., 2022).

Various coating preparation methods exist, including sol-gel, self-assembly, spraying, and dip-coating. The sol-gel method employs metal alkoxide hydrolysis and condensation reactions to form dense inorganic or organic-inorganic hybrid layers with strong adhesion, suitable for fine functional design. Self-assembly technology relies on non-covalent interactions (such as van der Waals forces and hydrogen bonds) to construct ordered multilayer structures at the nanoscale, thereby achieving functional superposition. Spraying and dip-coating are operationally simple and efficient, ideal for industrial-scale membrane treatment, while maintaining mild conditions to avoid thermal damage to membrane substrates. To prevent coating delamination during long-term operation and repeated cleaning, crosslinkers or low-temperature heat treatments are often applied to strengthen chemical bonding between coatings and membranes, enhancing mechanical durability (Chen, Li, Lin, et al., 2024).

The design of functional composite coatings has also matured. By combining inorganic nanoparticles with polymer matrices, multifunctional protective layers with hydrophilicity, antibacterial properties, and photocatalytic activity can be achieved. For instance, TiO_2/polyacrylic acid composite coatings retain photocatalytic activity while ensuring strong membrane adhesion and mechanical stability. Composite coatings can also modulate surface energy via nanoparticle surface modification, optimizing antifouling performance. Overall, coating technology plays a vital role in improving RO membrane antifouling performance and extending service life in power plants, owing to its process maturity, adaptability, and functional versatility (Zhao, 2022).

2.3 Plasma Treatment Technology

Plasma treatment is a physicochemical surface modification technique for reverse osmosis (RO) membranes that utilizes highly reactive species generated by gas discharge. Through radio frequency (RF) or microwave plasma, abundant electrons, ions, neutral free radicals, and excited-state molecules are produced. These active particles interact efficiently with membrane surfaces, inducing cleavage and recombination of surface chemical bonds while introducing various polar functional groups such as hydroxyl (–OH), carboxyl (–COOH), and amino ($–NH_2$) groups. This process significantly enhances membrane surface hydrophilicity and polarity. The improved hydrophilicity facilitates the formation of a stable water layer on the membrane surface, reducing the adsorption of hydrophobic contaminants and organic colloids, thereby mitigating fouling rates.

The plasma modification process is environmentally friendly, requiring no large quantities of chemical reagents or solvents, thus avoiding secondary pollution. Moreover, its mild operating conditions effectively preserve the membrane's pore structure and selectivity. Key process parameters—including discharge power density, treatment duration, gas type, and flow rate—critically influence modification outcomes. Oxygen plasma treatment is widely employed to introduce oxygen-containing functional groups, markedly improving membrane hydrophilicity. Nitrogen plasma can incorporate nitrogenous groups, enhancing antibacterial properties and chemical stability. Inert gases like argon primarily achieve surface cleaning and microstructure modulation through physical bombardment to remove surface contaminants.

In power plant water treatment systems, plasma-treated RO membranes demonstrate outstanding antiscaling performance by inhibiting the nucleation and adhesion of inorganic salts such as calcium carbonate and sulfates, effectively extending membrane module service life. Additionally, plasma treatment reduces biofilm formation rates by suppressing bacterial and algal attachment, thereby alleviating biofouling. Another crucial application of this technology is as a pretreatment step for graft polymerization and coating processes. By activating surface functional groups, plasma treatment improves the adhesion and uniformity of subsequent modification layers, ensuring long-term stability and durability (Yu et al., 2020).

Furthermore, advancements in plasma equipment have enabled the maturation of low-temperature and atmospheric-pressure plasma technologies, allowing continuous, large-scale industrial implementation. Future developments will integrate intelligent control systems for real-time parameter adjustment and monitoring, further enhancing modification efficiency and membrane performance consistency. In summary, plasma treatment has emerged as a vital technical approach for improving the antifouling performance and operational lifespan of RO membranes in power plants, owing to its high efficiency, environmental compatibility, and superior modification effects (Zhao, 2022).

3. Analysis of Anti-fouling and Cleaning Efficiency of RO Membrane Surface Modification Technologies

3.1 Significant Enhancement of Anti-fouling Capability

Surface-modified membranes demonstrate superior anti-fouling performance under complex feedwater conditions in power plants. The enhanced hydrophilicity and increased surface free energy of modified membranes reduce the contact angle of pollutants, making it difficult for contaminants to adhere firmly. Additionally, the smoother membrane surface morphology minimizes pollutant retention space, slowing deposition rates. The introduction of charge-regulation functionalities (e.g., negatively charged groups) effectively repels colloids or microorganisms with like charges, further improving anti-fouling performance. Meanwhile, antibacterial modification layers significantly delay biofilm formation, extending membrane module operational cycles. Various characterization techniques (e.g., contact angle measurements, surface energy tests, SEM/TEM imaging) confirm the improved surface properties and anti-fouling capabilities of modified membranes, laying the foundation for practical performance (Wang & Jia, 2021).

3.2 Improved Cleaning Efficiency

Surface modification enhances the membrane's inherent fouling resistance, substantially optimizing cleaning behavior. The weakened adhesion of pollutants allows easier removal by common cleaning agents (e.g., alkaline solutions, acids, or enzymes), improving cleaning recovery efficiency. The robust structural stability of modified membranes reduces damage during cleaning, enabling higher-concentration and higher-frequency cleaning strategies to prolong service life. Within cleaning cycles, modified membranes exhibit higher flux recovery rates, faster pressure restoration, and fewer residual contaminants, further reducing operational and maintenance costs. Moreover, some catalytically active modified membranes (e.g., TiO_2 photocatalytic membranes) can achieve self-degradation of fouling layers with cleaning agent assistance, reducing external cleaning frequency and supporting both environmental and economic goals.

3.3 Synergistic Effects

From a systemic perspective, membrane surface modification technologies synergize with operational management strategies and cleaning protocols. By coupling surface modification with system parameter optimization (e.g., transmembrane pressure, runtime, flow rate), overall fouling risks can be minimized. In practice, integrating modified membranes with online monitoring, intelligent early-warning systems, and automated cleaning setups enables intelligent operation modes based on real-time membrane status sensing. This facilitates preventive cleaning and proactive control, avoiding uncontrolled fouling accumulation. Additionally, modified membrane technologies contribute to energy consumption reduction. With mitigated fouling, membrane operational resistance decreases, energy recovery rates improve, and the overall efficiency of the RO system is substantially enhanced (An & Meng, 2021).

Conclusion

In summary, this study systematically investigates the principles and applications of RO membrane surface modification technologies in power plant water treatment systems. It evaluates the technical features and suitable scenarios of three mainstream modification approaches—graft polymerization, surface coating, and plasma treatment—alongside a comprehensive assessment of fouling control and cleaning performance. Surface modification significantly improves membrane surface characteristics, enhancing anti-fouling capability and cleaning responsiveness, thereby boosting system stability and cost-effectiveness. Among these, plasma treatment stands out for its eco-friendliness, high efficiency, and minimal substrate damage, demonstrating strong potential for challenging water quality conditions.

Conflict of Interest

The authors declare that they have no conflicts of interest to this work.

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