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Research Progress of Membrane Distillation Technology in Coal Chemical High Salt Wastewater Treatment

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Abstract: The treatment of high-salt wastewater from coal chemical processes has been a significant aspect of the pursuit of zero wastewater discharge. However, this treatment method is also the most energy-intensive process. Furthermore, the Erdos region is characterised by a scarcity of water, which presents a significant challenge for the coal chemical industry. Consequently, membrane distillation technology has emerged as a highly promising treatment option in recent years, attracting increasing research attention. The current limitations of membrane distillation technology in the treatment of high-salt wastewater from the coal chemical industry are still a topic of research. To further realise the application of this technology, research is mainly focused on aspects such as energy utilisation, component optimisation, material research and development, and economic evaluation. With the depth of research and the maturity of application, membrane distillation technology has become a promising new technology in the treatment of coal chemical high-salt wastewater.

Keywords: Membrane Distillation; Coal Chemical; High-Salt Wastewater; Zero Discharge Water.

1. Introduction

The coal chemical industry plays an integral role in China's economic growth and industrial output. However, the majority of such projects are concentrated in the northern regions on both sides of the Yellow River. This is due to the fragility of the ecological environment of the Yellow River Basin and the complex relationship between water resources, which have become significant constraints on the development of the coal chemical industry in these regions. Previously, the primary objective of wastewater treatment in coal chemical enterprises has been the purification of organic wastewater. However, the ongoing scarcity of water resources and the increasingly stringent environmental protection policies in the country have necessitated the achievement of zero discharge of coal chemical wastewater in industrial parks. Consequently, the treatment of coal chemical wastewater with a high salt content has become the primary objective of enterprise development. Furthermore, the coal chemical industry and other energy industries generate a considerable volume of toxic and harmful wastewater on an annual basis, necessitating prompt and effective treatment. However, the conventional wastewater treatment process frequently encounters limitations in terms of efficiency, complexity, operational and maintenance costs, and other challenges. Improper treatment can also result in adverse effects on the water environment, atmosphere, soil, and human health. Furthermore, Ordos City is experiencing a scarcity of water resources. The Yellow River is unable to replenish its water supply, and groundwater is the sole reliable source of water for industry, agriculture, and residential use in Ordos City. Consequently, the effective treatment and clean reuse of wastewater in energy industries, such as the coal chemical industry, is vital for the sustainable development of the energy industry [1, 2].

The total dissolved solids (TDS) in coal chemical wastewater typically range from 3000 to 15000 mg/L, which is considerably higher than the salt content of general wastewater. The principal inorganic ions present are Na^+, Cl^-, and SO_4^{2-}, which collectively account for over 90% of the total inorganic ions. The wastewater contains a variety of pollutants, including cyanide, sulphur cyanide, polycyclic aromatic compounds and heterocyclic compounds, as well as other toxic and harmful substances. The content of ammonia nitrogen and chemical oxygen demand (COD) is high, which increases the difficulty of wastewater treatment. The complexity of the coal chemical industry leads to a large amount of wastewater generation, which greatly increases the difficulty and cost of treatment [3].

2. Coal Chemical Industry High Salt Wastewater Treatment Process

The treatment of high salt wastewater from coal chemical industry usually requires the use of a combination of physical, chemical and biological technologies, including pre-treatment, biochemical treatment, deep treatment and evaporation and crystallisation steps, in order to achieve effective treatment and resourceful use of wastewater [4]. The treatment process flow diagram is shown in Figure 1.

2.1. Pre-treatment

The objective of the pre-treatment phase is to eliminate oil, suspended solids, phenols and ammonia and nitrogen from the wastewater. The most commonly employed techniques include oil separation, air flotation, phenol removal, ammonia evaporation and chemical precipitation. To illustrate, oil substances are removed through the processes of oil separation and air flotation, while the techniques employed in the removal of phenols encompass adsorption de-phenolisation, extraction de-phenolisation and water vapour de-phenolisation.

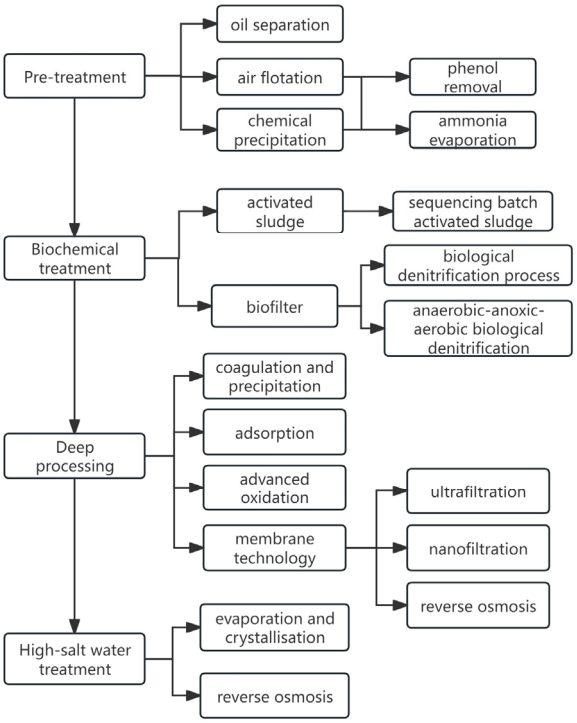


Figure 1. Coal chemical industry high salt wastewater treatment process

2.2. Biochemical Treatment

Biochemical treatment is the utilisation of microbial metabolism to degrade organic matter in wastewater, encompassing both aerobic and anaerobic processes. The most commonly employed processes include activated sludge, biofilter, sequencing batch activated sludge, biological denitrification process, anaerobic-anoxic-aerobic biological denitrification and phosphorus removal process. This step can markedly reduce the concentration of chemical oxygen demand (COD), biochemical oxygen demand (BOD5) and ammonia nitrogen in wastewater.

2.3. Deep Processing

Following biochemical treatment, wastewater may still contain organic matter that is resistant to biodegradation, necessitating further advanced treatment. The most commonly employed technologies include coagulation and precipitation, adsorption, advanced oxidation, and membrane technology (e.g. ultrafiltration, nanofiltration, reverse osmosis). These methods are effective in removing residual organic matter and colouration, ensuring that the wastewater meets the requisite standards for discharge or reuse.

2.4. High-salt Water Treatment

In the case of wastewater with a high salt content, membrane technologies such as reverse osmosis are typically employed for desalination purposes. The resulting concentrated water is then subjected to further processing through evaporation and crystallisation technology. This technology enables the conversion of high salt wastewater into solid crystalline salt, thereby achieving the objective of 'zero discharge' of wastewater. This step represents a crucial link in the process of wastewater resourcing and minimisation.

3. Membrane Distillation Technology in High Salt Wastewater Treatment

The treatment of high-salt water is a process that requires significant energy consumption and generates a considerable amount of wastewater. In light of the pressing need to conserve water resources, it is imperative to develop efficient and sustainable desalination techniques. Membrane distillation, a technology that has gained prominence in various industries, offers a promising solution. It is a highly efficient method of desalination that can be operated at room temperature, is easily miniaturised, and possesses other advantageous characteristics. Its applications in the coal chemical industry have demonstrated remarkable heat generation [5]. Membrane distillation (MD) is a membrane technology that employs a hydrophobic membrane for the separation of a mixed aqueous solution. The process is driven by a temperature difference across the membrane and a pressure gradient, facilitating the transfer of water vapour molecules from the hot to the cold end, where they liquefy. Despite the advances made in membrane distillation technology, several challenges remain. These include the relatively low flux of the membrane distillation system, the necessity for a membrane distillation module to provide the cold end, and the high energy consumption of the system. To address these issues, researchers are exploring various avenues, including:

3.1. Utilisation of Low-grade Energy Sources

Membrane distillation technology has the potential to utilise low-grade energy sources, including solar energy, geothermal energy and industrial waste heat, which are often not easily and efficiently utilised by conventional distillation technologies. The conversion of these energy sources into heat to drive the evaporation of water in the membrane distillation process represents an opportunity for energy savings. The current state of research on the utilisation of low-grade energy sources in membrane distillation technology demonstrates that scholars are engaged in the development and optimisation of methodologies for the utilisation of low-grade heat sources (e.g., waste heat or renewable resources) to drive membrane distillation processes. The principal objective of these studies is to enhance energy efficiency and reduce costs while minimising environmental impact. Utilisation of solar energy: Researchers are investigating methods of integrating solar energy into membrane distillation systems in an effective manner. Membrane distillation technologies that utilise solar energy as a low-grade energy source for desalination include both direct solar heating and the provision of thermal energy through solar collectors [6-8]. Furthermore, geothermal energy, which is a stable and sustainable energy source, has been investigated for use in the membrane distillation process. It has been demonstrated that the membrane distillation technology can be driven by geothermal energy gradient utilisation, thereby providing a stable heat source that is independent of weather conditions [9]. The optimal prospective form of energy utilisation in the treatment of coal chemical high salt wastewater is the utilisation of low-temperature waste heat generated in the production process engineering of coal chemical products. This waste heat is typically underutilised and can be converted into useful desalinated water by membrane distillation technology for secondary use of energy [10].

3.2. Membrane Materials and Module Design

In order to enhance the energy efficiency of membrane distillation systems, researchers are also developing innovative membrane materials and optimising membrane module designs with the objective of improving the thermal stability, flux and resistance to contamination of the membranes [11]. Researchers have sought to develop hydrophobic membranes that exhibit high flux, high strength, and resistance to wetting and contamination [12]. These materials include polypropylene (PP) [13], polyvinylidene fluoride (PVDF) [14] and polytetrafluoroethylene (PTFE) [15], as well as conventional membrane materials modified by the addition of nanomaterials, including silica, zinc oxide, carbon nanotubes and graphene. Conversely, researchers have investigated alternative membrane module designs, including flat plate[16], hollow fibre [17] and helical rolled [18], with the objective of enhancing heat transfer efficiency and reducing energy consumption. These designs are intended to optimise fluid dynamics and thermal management, thereby improving the performance of the membrane distillation process [19]. Furthermore, in order to enhance the mass transfer process, researchers have conducted experiments utilising internal/external field aids, including electric, magnetic or acoustic fields [20]. Additionally, they have explored the potential of multistage and multi-effect membrane distillation systems to improve energy efficiency [21]. These systems are capable of achieving multiple uses of heat within a single module, thereby significantly reducing energy consumption [22]. Furthermore, surface modification techniques have been employed to enhance the hydrophobicity of membrane materials, mitigate wetting and contamination, and thus optimise membrane performance and longevity [23]. Nanofibre electrospinning techniques have been employed to fabricate nanofibre membranes with a high specific surface area, high porosity and adjustable pore size, with the objective of attaining enhanced performance compared to membranes prepared through conventional phase conversion methods [24]. Collectively, these research components have contributed to advancements in membrane distillation technology with respect to energy efficiency, economics and environmental impact.

3.3. System Optimisation and Integration

System optimisation and integration represent pivotal areas of inquiry within the domain of membrane distillation technology, encompassing a multitude of research avenues. This encompasses the optimisation of operational parameters, whereby the impact of variables such as feed temperature, flow rate and vacuum on the process is examined to ascertain the optimal operating conditions [25]. Furthermore, membrane distillation has been integrated with other separation technologies, including reverse osmosis, electrodialysis and crystallisers, to form composite systems with the objective of improving overall performance [26, 27]. Process simulation and control: The objective is to design more efficient membrane distillation systems with automated control through numerical simulation and optimisation [28]. Additionally, research has been conducted on the recovery of energy, particularly the recovery of the latent heat of evaporation and condensation through heat pump technology, with the aim of reducing energy consumption [29].

3.4. Economic and Sustainability Assessment

In the field of membrane distillation technology, research on the assessment of economic and sustainability factors is becoming a pivotal driver of technological advancement. The research encompasses techno-economic analyses, which entail the evaluation of the membrane distillation process in terms of investment feasibility. This includes an assessment of the performance and cost-effectiveness of membranes under diverse operational conditions. Concurrently, researchers are investigating the potential integration of renewable energy sources, such as solar and geothermal, into membrane distillation systems as a means of enhancing the sustainability of such systems. In terms of energy efficiency and quality, membrane distillation is being compared with other desalination technologies, such as reverse osmosis and multi-effect distillation, in order to assess their performance in terms of energy use, quality and fouling susceptibility [30]. Furthermore, cost-benefit analyses of innovative membrane materials, such as ultra-high flux membranes, represent a significant area of research [24]. This is due to the potential impact of such materials on cost while simultaneously enhancing performance. Life cycle assessment (LCA) is another assessment tool employed to evaluate the environmental impact of membrane distillation systems throughout the process, from production to disposal [31]. Additionally, researchers are examining integrated and cleaner production processes for membrane distillation technologies, as well as the economic and environmental sustainability of these technologies in diverse application contexts. Additionally, thermo-economic and environmental analyses are conducted to evaluate the performance of membrane distillation based on energy, fire-use, economic and environmental parameters, including gain-to-output ratio (GOR), specific energy consumption (SEC), fire-use efficiency and environmental impacts. The economic assessment, in contrast, concentrates on the cost-effectiveness of producing potable water from brackish water using a membrane distillation system, taking into account pivotal parameters such as plant size, waste heat utilisation and membrane permeability [32]. These research components not only facilitate the optimisation of membrane distillation technology, but also encourage the advancement of the technology in terms of economic and environmental sustainability for broader application in the field of water treatment and desalination.

4. Conclusion and Outlook

Membrane distillation technology demonstrates considerable promise in the treatment of high-salt wastewater generated by coal chemical processes. This is due to the technology's high efficiency in desalination and low energy consumption during operation. The technology employs thermal energy to separate water vapour through hydrophobic microporous membranes, thereby achieving an efficient separation of salts. Furthermore, it is capable of operating at low temperatures, utilising waste heat or low-grade heat sources to reduce energy consumption. The integration of membrane distillation with other water treatment technologies enhances the overall efficiency of the system. The development of membrane distillation technology is being driven by the implementation of stringent environmental policies, particularly in relation to its capacity to achieve near-zero wastewater discharge. The development

of new membrane materials and optimised membrane module designs has led to improvements in system efficiency and durability. With technological advances, the number of applications of membrane distillation in the coal chemical industry is gradually increasing, and the market potential is significant. Researchers are attempting to address the fouling issue and enhance the stability and economic viability of the system. In conclusion, membrane distillation technology has a broad range of potential applications in coal chemical wastewater treatment due to its notable advantages.

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